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Selective offload capability simulation (SOCS) : an analysis of high-density storage configurations

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THESIS

SELECTIVE OFFLOAD CAPABILITY SIMULATION (SOCS): AN ANALYSIS OF HIGH DENSITY STORAGE CONFIGURATIONS

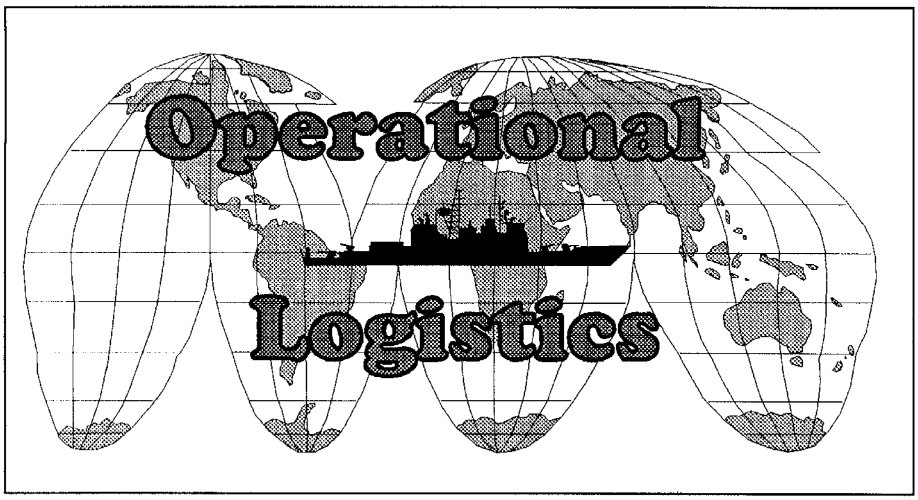
by

Frank W. Futcher

September 2003

Thesis Advisor: Kevin R. Gue
Second Reader: Arnold H. Buss

Amateurs discuss strategy,
Professionals study logistics



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Future sea bases, such as the Maritime Prepositioning Force (Future), will serve as key distribution nodes and must be able to sustain forces ashore and selectively offload supplies from storerooms quickly and efficiently. Current MPF ships maximize the available cargo storage onboard and have little ability to selectively offload supplies. To make selective offload a reality, MPF(F) requires lower stowage densities and new technologies to efficiently move items, especially for those supplies needed in direct support of forces ashore. The difficult questions are how dense and in what configurations MPF(F) storerooms can be packed, and how items should be retrieved in order to selectively offload supplies and provide acceptable response time.

We analyze the trade-off between storage density and mean retrieval time in a dynamic environment for different storage densities and configurations in notional storerooms aboard a future sea base. We examine two demand scenarios and two different retrieval rules to determine how each storage configuration responds to retrieval requests over time. Our results provide insight into the types of storeroom configurations that provide the best mean retrieval times and how a simple retrieval rule can significantly reduce mean retrieval time under certain demand conditions.

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SELECTIVE OFFLOAD CAPABILITY SIMULATION (SOCS): AN ANALYSIS OF HIGH DENSITY STORAGE CONFIGURATIONS

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DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. In addition, every effort has been made to ensure that the computer programs developed by the author were free from error. However, due to the large number of storage system configurations and densities explored within this thesis, the author cannot guarantee that they are all in fact error free and as a result, the programs cannot be considered validated. Future users should first verify the programs and their intended use before utilizing these programs in additional applications beyond that used in this thesis.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF SYMBOLS, ACRONYMS AND/OR ABBREVIATIONS

AAV	Amphibious Assault Vehicle
AAAV	Advanced Amphibious Assault Vehicle
ACE	Air Combat Element
AS/RS	Automated Storage and Retrieval System
AVCAL	Aviation Consolidate Allowance List
CNA	Center for Naval Analyses
CRN	Common Random Number
EMW	Expeditionary Maneuver Warfare
HMMWV	High Mobility, Multi-Wheeled Vehicle
LCAC	Landing Craft, Air Cushion
LCS	Littoral Combat Ship
LMSR	Large, Medium Speed, Roll-On/Roll-Off
MAGTF	Marine Air Ground Task Force
MCCDC	Marine Corps Combat Development Command
MAB	Marine Amphibious Brigade
MCB	Multiple Comparison with the Best
MCP	Multiple Comparison Procedure
MEB	Marine Expeditionary Brigade
MEU	Marine Expeditionary Unit
MPF	Marine Prepositioning Force
MPF(F)	Marine Prepositioning Force (Future)
MPSRON	Maritime Prepositioning Ship Squadron
MRE	Meal, Ready-To-Eat
NAVSTORS	Naval Stowage and Retrieval System
NTPS	Near Term Prepositioning Ship
OMFTS	Operational Maneuver From the Sea
RO/RO	Roll-on/Roll-off
RPC	Robotic Payload Carrier
SBL	Sea Based Logistics
SPI	Standard Payload Interface
SOCS	Selective Offload Capability Simulation
STOM	Ship-to-Objective Maneuver
T/E	Table of Equipment
VHD	Very High Density

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This thesis would not have been possible without the advice and guidance of Professor Kevin Gue, my thesis advisor. His ideas and insightful work in the areas of storage configurations and stowage density provided the basis for my thesis and will be of great benefit to the Department of Defense. I must also thank my second reader, Professor Arnie Buss and Professor Paul Sanchez for their input and help in pushing this thesis in the right direction, and Professor Susan Sanchez for her patience and assistance in getting the analysis right.

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EXECUTIVE SUMMARY

Future sea bases, such as the Maritime Prepositioning Force (Future) (MPF(F)), must serve as the primary forward deployed distribution nodes that directly support and sustain forces ashore. This requires the future MPF to be able to locate and retrieve any piece of equipment or commodity onboard and deliver it to the landing force, where and when needed. This capability is called selective offload and in this thesis refers to the sustainment of forces ashore rather than the tactical delivery of roll-on, roll-off cargo (i.e. placing the AAAV's, tanks, and other vehicles ashore in a ready to fight configuration).

Current MPF ships maximize the available cargo storage onboard (i.e. many storage spaces are 100% full) and have little ability to selectively offload supplies. Without a selective offload capability, MPF(F) will be unable to break the current dependence on shore staging, to reconfigure internal loads (i.e. equipment of supplies) for offload, or to adequately decrease the logistical tail ashore. To make selective offload a reality, MPF(F) requires lower stowage densities and new technologies such as automated storage and retrieval systems (AS/RS) to efficiently move items, especially for those supplies needed in direct support of forces ashore.

However, MPF(F) must be able to store as much material as possible to fulfill its role as the primary provider of supplies to forces ashore. In addition, MPF(F) must be able to retrieve items quickly since future sea bases are likely to operate over-the-horizon with extended lines of supply and communication. The problem is to find the right balance between competing objectives, which is directly related to the density of items in storage, the configuration of those items, and the methods in which individual items are selectively retrieved.

We analyze the trade-off between storage density and mean retrieval time in a dynamic environment for different storage densities and configurations in notional MPF(F) storerooms with single input/output points. In addition, we examine two demand scenarios and two different retrieval rules to determine how each storage configuration responds to retrieval requests over time. Small amounts of density are traded for improved response times by constructing storeroom configurations that provide slightly higher levels of accessibility.

To quantify the trade-off, we used the mean retrieval time to compare each storage system under each of four different scenarios. A lower mean retrieval time for any particular storage system implies that the system can retrieve any randomly selected pallet over time more quickly than an alternate system.

We created two models to examine this problem; a conceptual model, termed the *Storeroom Model*, to represent the storage systems and a simulation model, termed the *Selective Offload Capability Simulation (SOCS)*, to capture each storage system's mean retrieval time under differing conditions. The Storeroom model represents notional very high density storerooms aboard MPF(F). The SOCS model simulates the operation of each storage system by subjecting it to a stream of retrieval requests. The system must select a pallet for retrieval, reposition any pallets that block access to the selected pallet, retrieve the selected pallet, and then return the pallets to locations in the storeroom. This is done repeatedly for each storage system over time to estimate the steady state mean retrieval time.

Given the requirement that future sea bases must be able to sustain a force ashore, our results show that the designs with storage densities between 70% and 85% better support the requirements for selective offload and sustainability despite the slightly higher expected retrieval times than storerooms with greater access and lower density. Configurations with storage densities greater than 85% had mean retrieval times that were much higher than those in the 70%-85% density range because the storage systems had to make too many moves internally to reposition its contents to get to any one pallet. Configurations with storage densities less than 70%, on the other hand, substantially reduce the MPF(F)'s primary mission of prepositioning material for the sustainment of forward deployed forces ashore. Configurations with low storage densities should be reserved for the most time critical and sensitive items or for items that are not suitable for storage and retrieval in an automated system.

Our results also show that small square or near square storage configurations provide the best mean retrieval times under any of the conditions examined. In addition, a simple retrieval rule significantly reduces mean retrieval times for storerooms with storage densities above 70%. The total net reduction in mean retrieval time was greater for higher density storage systems while there was no reduction in mean retrieval time for storerooms with storage densities less than 70%.

Future trade-off analyses with regard to sea base storeroom design decisions should take into account that the higher density designs (i.e. those between 70% and 85%) can provide mean retrieval times that are comparable to lower density storage system. The higher density designs provide a bigger payoff in sustainment with only a slightly higher mean retrieval time. Not only does this still support a selective offload capability but also enhances the sea base's overall sustainment capability.

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I. INTRODUCTION

A. CONCEPTUAL OVERVIEW

With the recent release of “Sea Power 21”, the Navy set out its vision of how the Navy will organize, integrate, and transform itself to meet the challenges of the 21st century. One of the fundamental concepts of that vision is Sea Basing, which involves operational maneuver, power projection, accelerated deployment and employment times, and operational independence in support of a joint force. [Ref 1] Utilizing the vast open sea as a maneuver space lies at the very heart of Sea Power 21. Sea Basing minimizes the need to build up forces and supplies ashore while providing security and enhanced mobility.

One of the key capabilities of the future sea base will be to provide enhanced on-scene endurance while minimizing the logistics footprint ashore. Sea Basing will enable the full implementation and execution of Marine Corps warfare doctrines for Expeditionary Maneuver Warfare (EMW), Operational Maneuver from the Sea (OMFTS), Sea Basing, and Ship-to-Objective-Maneuver (STOM). Although the future sea base will be comprised of numerous platforms, the Maritime Prepositioned Force (Future) (MPF(F)) ships will be integral to the future sea base. These prepositioned squadrons, based in the Mediterranean, Pacific and Indian Oceans, will enable the future sea base to sustain a Marine Expeditionary Brigade (MEB) in a variety of conflicts for 30 days. [Ref 2]

MPF(F) will provide four capabilities that are not resident in the current fleet of MPF ships: (1) at-sea arrival and assembly, (2) direct support of the assault echelon of the Assault Task Force (ATF), (3) indefinite sustainment of the landing force, and (4) at-sea reconstitution and redeployment [Ref 10]. These enhanced capabilities will allow future Expeditionary Forces to conduct a variety of missions while providing the necessary logistics support.

Future operational Navy and Marine Corps concepts such as Expeditionary Maneuver Warfare (EMW), Operational Maneuver from the Sea (OMFTS), Sea Basing, and Ship-to-Objective-Maneuver (STOM), require substantial logistics and sustainment capabilities to be resident on the sea base. In addition to the shear mass of materials required to support a MEB ashore, individual Marine units will require custom-tailored packages depending on their anticipated needs. Therefore MPF(F) must have the ability to selectively offload MEB stores, medical supplies, ordnance, parts, and equipment from storerooms quickly and efficiently and then transfer these materials to the flight deck or well-deck for dispatch. A selective offload capability allows MPF(F) to offload any type and quantity of equipment or cargo, at any time.

Selective offload is about providing a quick and responsive logistics system; a system that provides the instantaneous retrieval and delivery of selected supplies to forces ashore in palletized loads. We use the term selective offload within this context rather than selective offload associated with the tactical delivery of Roll-on, Roll-off (RO/RO) cargo (tanks, trucks, HMMWV's, AAV's, etc.).

Current MPF ships maximize the available cargo cube space onboard. As a result, the current MPF ships have little ability to selectively offload equipment or supplies because many of the items onboard are simply not accessible. Without a large secure port with an ample arrival and assembly area to support a full offload, current MPF platforms cannot support Marine-Air-Ground Task Force (MAGTF) operations. MPF(F), however, will be designed to serve as the primary distribution center providing ready issue material to forces ashore. Therefore, future MPF ships must be designed with a selective offload capability, and this issue is directly related to the density of items in storage, the configuration of the stored items, and the methods in which individual items are selectively retrieved.

B. BACKGROUND

1. The Maritime Preposition Force (MPF) Program

In the early 1980's, the United States identified a need for a sustainable presence beyond the forward-deployed capabilities of the carrier battle group or amphibious readiness group. In response to this new requirement, the Navy and Marine Corps created the Near Term Prepositioning Ship (NTPS) program that could support a Marine Amphibious Brigade (MAB) for 30 days. [Ref 2] The importance of strategic sealift was formally recognized with the birth of this program. The NTPS program later became the Maritime Prepositioning Ship (MPS) program in 1984. The MPS program was comprised of 13 commercial RO/RO cargo and container ships divided into three squadrons. The squadrons are used to strategically preposition a Marine Air Ground Task Force's supplies, vehicles and equipment in key locations for use during times of crisis. Figure 1 provides the locations of the current MPS squadrons. [Ref 2]

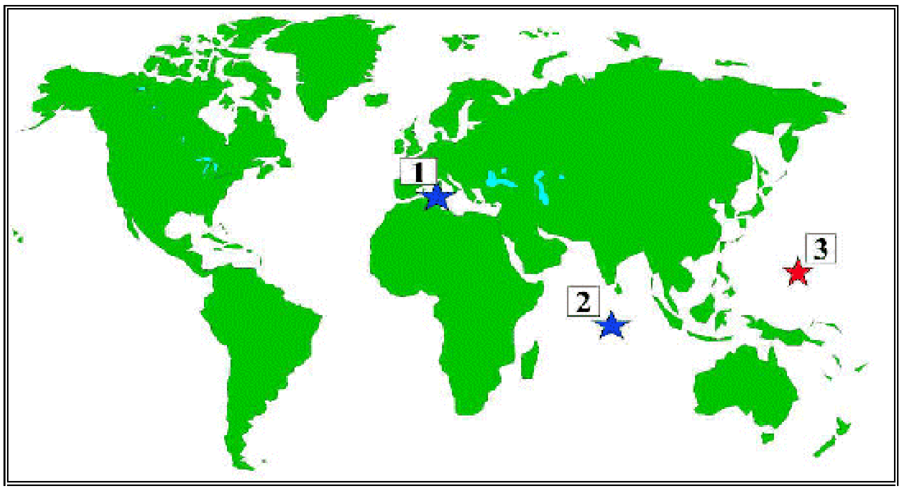

Figure 1 Current MPF Squadron Locations. (From: Ref 2)

The current MPS program requires a non-hostile environment and extensive port facilities to accommodate the deep draft of the MPF ships and enough port space to allow Marines to assemble and make preparations for combat. In addition, a secure and friendly airfield is necessary to support the Marine Amphibious Group Task Force (MAGTF) Air Combat Element (ACE) near the objective. All of these key facilities including ample space to conduct arrival and assembly were available and utilized during Operation Iraqi Freedom. For example, during Operation Iraqi Freedom, two squadrons of MPF ships, a total of 11 ships, were ordered to the Kuwaiti port of Ash Shu'aybah and offloaded from 6 January to 4 February. [Ref 3] Since current MPF cannot conduct arrival and assemble at sea, the Kuwait desert was utilized as a massive staging area and parking lot for the MPF gear as Figure 2 illustrates. [Ref 4] What if countries deny the United States and its allies use of those assets, as did Turkey during Operation Iraqi Freedom?

Figure 2 5th Marine Regiment Staging Gear from MPF Ships. (From: Ref 4)

The current Maritime Prepositioning Force lacks the capability to support the Marine Corps concepts of Expeditionary Maneuver Warfare (EMW), Operational Maneuver from the Sea (OMFTS), Ship to Objective Maneuver (STOM), and Sea Basing, and satisfy the other required operational capabilities defined for MPF(F). [Ref 24] These concepts focus on the ability to operate from the sea with little or no supporting logistical or command infrastructure ashore. Therefore, future MPF ships must be able to project forces directly from the sea base to the objective ashore without an operational pause at the beachhead and assemble the forces before moving inland to the objective. The goal is to enhance combat effectiveness by utilizing highly mobile forces by sea or air and a high operational tempo. The current MPF program cannot support these and other emerging concepts. It simply lacks any of the capabilities necessary to base forces afloat, project them ashore, maneuver them to varying objectives, sustain them from the sea, or reset them.

Future MPF operations must meet the tenets of 'Sea Power 21': Expeditionary Maneuver Warfare (EMW), Operational Manuever from the Sea (OMFTS), Ship to Objective Manuever (STOM), and Sea Basing. The following provides a short summary of those concepts.

2. Sea Power 21

"Sea Power 21" is the United States Navy's roadmap to ensure the 21st Century Navy and Marine Corps team is a "networked, jointly integrated, sea-based power projection force, assuring coalition and joint force access and protecting America's interests any where in the world." [Ref 1] The operational concepts of Sea Strike, Sea

Shield, and Sea Basing provide the basis for "Sea Power 21." The Global Concept Of Operations is to widely disperse combat power from a variety of platforms all over the globe. This combat power is tied to a force structure that includes Carrier Strike Groups, Expeditionary Strike Groups, and Missile-defense Surface Action Groups. The generation and projection of combat power is directly tied to the operational concept of sea basing.

a. Sea Basing: Projecting Joint Operational Independence

Operational maneuver at and from the sea is one of the key aspects to the concept of sea basing. If the Navy can control the sea space, the joint force commander is provided a safe base from which to project power. Many functions like command and control, fire support, and logistics, which used to move ashore with the landing forces, would be resident in the sea base. [Ref 1] This concept of operations requires each of these functions to be flexible to sufficiently support the efforts ashore with as little delay as possible. In past wars and contingencies, mountains of supplies were moved ashore to support the landing forces. The MPF ships are the assets that strategically place these supplies in locations around the globe ready for movement to the nearest location in support of the landing forces. Since future logistics functions will be retained on the sea base, future MPF ships must be able to operate as a key distribution node from which forces ashore are sustained. MPF(F) retains the mountain of supplies but the mountain will be located over-the-horizon far from the forces it supports.

This concept requires future Navy assets like the Littoral Combat ship, DD-X, and CVN-X to maintain complete control of the area around the MPF(F) sea base while ensuring the long lines of communication and supply are maintained. The idea of supporting forces from over-the-horizon requires MPF(F) to serve as the conduit for logistics support and sustainment, and to employ an automated inventory capability. [Ref 24, p. 2]. In addition, the MPF(F) cargo spaces "should be designed with sufficient flexibility to permit reconfiguration" and "should be automated to the greatest extent possible to promote significant manpower and training cost savings." [Ref 24, p. 4) These statements highlight the shortcomings with current material handling and stowage systems and requires the insertion of key technological advancements such as automated storage and retrieval systems (AS/RS), higher speed cargo handling systems, higher density stowage systems, and even advanced robotic planar agents that reduce the Navy's current reliance on forklifts and forklift drivers. In addition, the MPF(F) sea bases will require systematic replenishment should operations ashore continue for more than 15 days since MPF ships are only capable supporting a MEB for approximately 30 days. This implies that the sea base must not only be able to selectively offload and access supplies with which it begins an operation, but also be capable of receiving, processing, storing, and transporting supplies forward to forces ashore. MPF(F) will serve as the hub for the storage and distribution of all supplies directly supporting Marine Corps deployed forces.

3. Marine Corps Strategy 21

The United States Marine Corps Strategy 21 forms the vision and the basis for how the Marine Corps will operate and fight in future wars or military operations other than war. [Ref 5]

a. Expeditionary Maneuver Warfare

Expeditionary Maneuver Warfare is the Marine Corps' capstone concept that guides the Marine Corps into the 21st Century. As outlined in Marine Corps Strategy 21, Expeditionary Maneuver Warfare (EMW) provides the foundation for the methods, which the Marine Corps will organize, deploy and conduct future operations. It highlights the importance of maneuverability from which all future Marine Corps concepts are based and how future operations will be conducted. [Ref 6]

b. Operational Maneuver from the Sea

OMFTS lies at the heart of EMW and emphasizes the importance maneuver to sufficiently project power from the sea. The OMFTS concept creates a high operational tempo that doesn't allow an enemy to mass his forces and creates weakness in the enemy's defense. The current Marine Corps operations rely on the traditional beach assault followed by a logistics build up and an increase in combat power before moving against the objective. OMFTS requires an enemy to defend many different objectives and spread his forces rather than concentrating forces in the most likely traditional amphibious assault location. In addition, greater maneuverability offers greater tactical surprise as to the location of the actual assault, which allows the Marine Corps to concentrate forces at the decisive point, while denying the enemy the ability to concentrate their forces. [Ref 7] This requires the sea base to receive, store, maintain, manage and deploy all of the equipment and supplies to sustain a landing force which current MPF ships are unable to do. [Ref 24]

c. *Ship-To-Objective Maneuver*

Ship-to-Objective-Maneuver (STOM) is a key application of OMFTS. It is an application of OMFTS that allows future Marine forces to maneuver in tactical formation from the moment they depart the sea base until they reach the tactical objective. All maneuver operations are supported from the sea base with the goal of reducing or eliminating the need for support functions ashore, which are more vulnerable to attack than under the protective cover of a sea base. Ship-to-Objective-Maneuver utilizes both surface and vertical lift assets (i.e. CH-53's, V-22's, and LCAC's) to attack enemy objectives directly from the sea base instead of waiting for the build up of combat power ashore before launching an assault. [Ref 8] Current MPF ships are unable to support either of the OMFTS and STOM concepts of operations that require assaults directly against enemy objectives from the sea base. Before an assault against an objective can take place, current MPF ships must unload all of the supplies and equipment at a safe port. [Ref 24]

d. *Sea Basing*

Sea Basing is about independence, mobility and maneuver. The success of EMW, STOM and OMFTS is based on the ability of the sea base to effectively operate the command and control and logistics functions of the assault force. If the sea base is unable to perform this function, the concepts of OMFTS and STOM cannot be achieved.

e. *The Maritime Preposition Force 2010*

The future maritime pre-positioning force (MPF(F)) and ships of the amphibious task force (ATF) will form the core of the future sea base. The MPF(F) and ATF team are essential to the Navy's efforts to conduct EMW and OMFTS. The Maritime Prepositioning Force 2010 and Beyond concept describes how the future MPF ship will provide the forward presence and power projection capabilities required to support the Marine Corps capstone concepts like EMW, OMFTS, and Sea Basing. Those primary MPF(F) capabilities will include force closure, amphibious task force integration, indefinite sustainment, and reconstitution (now called resetting the force) and redeployment. [Ref 10]

Force closure provides for the at-sea arrival and assembly of the MEB, which eliminates the need for secure ports and airfields. Amphibious task force (ATF) integration provides the capability to selectively offload MEB force packages to reinforce the assault echelon of an ATF. Indefinite sustainment provides the sea based logistics capabilities in accordance with the principles of OMFTS. Finally, reconstitution and redeployment provide the ability to quickly backload the MPF(F) MAGTF and immediately re-deploy in assigned follow-on missions. [Ref 10]

C. THE NEED FOR A SELECTIVE OFFLOAD CAPABILITY

The future MPF must be able to locate and deliver any piece of equipment or commodity onboard to support the landing forces ashore, where and when needed. This capability has been termed selective offload. Without a selective offload capability, MPF(F) will be unable to break the current dependence on shore staging, reconfigure internal loads (i.e. equipment of supplies) for offload, or adequately decrease total manpower ashore required to support and sustain forces ashore. Selective offload is intended to eliminate the need for large volumes of supplies to be tied to and in close proximity to the landing force.

1. Selective Offload Defined

Selective offload can be defined and further broken down into two primary areas: selective offload of roll-on, roll-off (RO/RO) cargo and the selective offload of dry cargo. The principal cargo carried by MPF(F) will be the RO/RO cargo (AAAV's, tanks, trucks, HMMWV, etc.). This type of cargo must be accessible for selective offload in a tactical configuration that allows for the arrival of equipment and personnel at an objective in the right quantity and sequence and completely prepared for immediate operations. MPF(F) must be able to access, reposition and deliver any one of the vehicle types to a shipboard staging area for offload while at-sea via LCACs, vertical lift assets or while pierside via the RO/RO ramps. This allows the Joint Force Commander to adjust his force to the mission requirement.

The term selective offload is also used to refer to the selective retrieval and delivery of supplies to forces ashore in palletized loads. This type of selective offload is associated with the sustainment of forces ashore rather than the tactical delivery of RO/RO cargo. We use the term selective offload in this context.

MPF(F) will contain adequate supplies to support a MEB for at least 30 days, including Meals, Ready-To-Eat (MRE's), ammunition, repair parts, medical supplies, and test equipment, tools, and consumables. These types of items are required by maneuver units to operate ashore or by the support elements of the sea base needed in direct support of the maneuver elements. This requires MPF(F) to have a selective offload capability that can access certain items with little if any delay.

2. Levels of Accessibility

The prepositioned stock of a MEB's equipment and supplies on MPF(F) can be broken down into three levels of accessibility [Ref 11]. The first level is the sea based Power Projection Increment or First Increment. The equipment and supplies in this increment represent the core capability of MPF(F). It is made up of the equipment and supplies (consumables such as fuel, water, food, ammunition, parts, etc.) for forces ashore and for the sea based support element. Those items include not only the Table of Equipment (T/E) items required for support functions of the sea base like command and control, messing, or planning but also the Aviation Consolidated Allowance List (AVCAL) items required to maintain the equipment of forces ashore and afloat. All of the items included in this category must be accessible through various selective offload capabilities and require minimal repositioning of other assets to gain access. This category is the most time sensitive in terms of response and would probably be the least densely stored of the three categories.

The second level of accessibility is the Support or Contingency Operations Increment or the Second Increment. Items in this category are required to perform special missions and include those items such habitability, power generation, water purification and water distribution equipment. These items allow MPF(F) to support contingency or humanitarian operations and other similar types of tasking. All of the items included in this category must be accessible and should require a limited amount of repositioning of other assets to gain access. These types of items still require a selective offload capability but without the time-sensitive constraints of items in the Sea based Power Projection Increment. [Ref 11]

The third level of accessibility is the Sustained Operations Ashore Increment or Third Increment. This last set of items include tents, generators, bulk construction material, and additional line-haul/long-haul material and allow maneuver units either to extend their operational distance from the sea base or to extend the duration of operations ashore. None of the items in this category need to be readily accessible and need no selective offload capability. These items could be densely packed to maximize available MPF(F) storage space. [Ref 11]

3. Selective Offload in a Reduced Manning Environment

Current methods to selectively offload any specific item, package, pallet, or container from a ship typically require significant amounts of labor utilizing forklifts or literally moving items by hand. When an LHD, for example, receives stores from a CLF ship, the LHD uses large working parties to breakdown the pallets and move items by hand down to storerooms in the ship. As those items are needed, the reverse is done. This process is called the strike-up and strike-down of material.

MPF(F) must be able to access and selectively offload any of the dry cargo stowed onboard with smaller manning levels and capable of being manned by civilian crews.[Ref 24] Given the amount of cargo stored on a single MPF ships, this task will not be easily accomplished. The Center for Naval Analyses (CNA) estimated that a single MPF(F) would be required to carry more than 600 pallets of general stores, another 2,970 shore tons of ordnance, and up to 484 containers.[Ref 13, p.26] Given the current vision of manning future ships with smaller crews, one can see that utilizing large working parties to move items from one point to another is probably not viable.

4. Automated Stowage and Retrieval Systems

The Naval Sea Systems Command (NAVSEA) and the Office of Naval Research (ONR) have been funding research to find new technologies and systems that support reduced manning and maintenance initiatives. Some of the technologies being explored include auto tracking, planning and warehousing, load handling and movement equipment, cargo stowage, and improved stowage density/selective offload. [Ref 12] Given the reduced manning initiatives and the need for an extremely robust logistics capability on MPF(F), we assume that MPF(F) will have either robotic agents that enter storerooms to move, position, or reposition pallets in storerooms or an automated storage and retrieval system (AS/RS).

An Automated Storage and Retrieval System (AS/RS) is a commercially available technology originally designed to automate many manufacturing and warehousing functions. Utilizing AS/RS onboard future sea base platforms is a significant design challenge because it must take into account ship motion, blast and shock requirements, weight limitations, and be able to stow loads in some standardized fashion. In addition, the AS/RS must be designed for easy access throughout the system for maintenance and repair.

An AS/RS system allows for significant reductions in manpower. Sailors would no longer need to conduct inventories, retrieve items, or restack and move items to retrieve other items by hand. Most of these systems are capable of integrating load identification, location and inventory data with identification tags on both the standardized load containers or the items themselves. In addition, the systems are able to accept retrieval requests, provide reports and communicate with other logistics systems on the ships. All of this relates directly back to the goal of reducing manning levels on ships. By removing human intervention from the process, sailors can be better utilized to perform more vital shipboard operations.

Since MPF(F) is likely to be "automated to the greatest extent possible to promote significant manpower and training cost savings", we assume MPF(F) will utilize a fully automated stowage and retrieval systems onboard. [Ref 24] One promising shipboard AS/RS system is the NAVSTORS system (Naval Stowage and Retrieval System). [Ref 14] NAVSTORS is designed to perform weapons handling operations in the holds and magazines in Nimitz class and CVN-21 class aircraft carriers. This is a high-density storage system that could be adapted for MPF(F) to enable a selective offload capability. [Ref 14]

MPF(F), like current MPF ships, will have almost all of its cargo palletized or containerized, with the exception of the RO/RO cargo. Much of it will be stowed in storerooms of varying sizes and densities throughout the ship; some near elevators and close to the flight deck or well deck, and others far away. Current MPF operations, as discussed earlier, require extensive port facilities and ample space to support offload and assembly. Current MPF cargo handling operations are extremely complicated, labor intensive and time-consuming. Most of the cargo is moved by either fork truck, crane, or by hand (i.e. pallet jack or even by an individual) and is not done without difficulty especially in heavy seas. Utilizing AS/RS technologies like NAVSTORS may not only eliminate manual labor involved in current stowage and retrieval operations but also improve the efficiency of the operation, allow for much greater stowage densities, and allow for the movement of material in higher sea states.

D. RESEARCH OBJECTIVES

The concepts of EMW, OMFTS, STOM and Sea Basing will require a distribution of supplies to operational forces located at multiple objectives and spread out over greater geographic areas and longer distances. The key to MPF(F)'s ability to effectively serve as a sea base will be its ability to identify and prioritize sustainment requirements, rapidly locate and access required cargo, consolidate and package those items, and prepare them for delivery to the forces ashore. This capability will reduce the logistics footprint ashore.

1. Problem Definition

Although current MPF ships store material in a variety of ways, the focus of this study will be on the selective offload of items from a set of different configurations offering varying levels of accessibility and the ability of different storage systems to respond to a series of randomly requested pallets. It is envisioned that most material will be stored in standard load sizes to enable or enhance the selective offload capabilities and stowed and retrieved via an AS/RS.

Selective offload does not necessarily refer to instantaneous offload or retrieval. Instead there are degrees of selective offload capabilities. For example, a pallet can be selectively retrieved without delay (e.g. a pallet can be instantly located, retrieved, and offloaded in support of forces ashore without having to reposition other assets thereby 'delaying' the nominal best delivery time). Alternatively, a pallet can be retrieved with a delay. In other words, a pallet can be located, and retrieved and offloaded but the retrieval requires a repositioning of other assets, which increases response time. The delay or expected retrieval time of any system is directly related to the level of accessibility the system offers. Densely stored items offer less accessibility than do less densely stored items. Therefore, selective offload is directly related to accessibility and improving accessibility generally comes at the cost of a lower storage density.

Current MPF ships are densely packed with stow factors (the ratio of occupied space to available space) approaching one. A storeroom with no additional storage space would have a stow factor of one and provides no ability to selectively offload. Extremely dense storerooms do not support the concept of selective offload except for items required in support of sustained operations ashore or for standard items like MRE's. In cases like this, it makes sense to store single, high-demand items together to maximize the available cargo cube space. As items are needed, they can be pulled from the front for offload with no shifting of other items.

A low storage density, on the other hand, results in unused space and possibly a smaller volume of material carried that could decrease MPF(F)'s primary sustainment capability. In a storage system that carries many different types of line items, a lower storage density is necessary to provide space to shift or move other items to gain access to any other item. The storage density must be dense enough to maximize use of the available cargo cube space but not so dense as to increase response times to retrieve any particular pallet.

Figure 3 illustrates an example of an extremely dense 4 x 4 storeroom with many different types of items. The storeroom can hold a maximum of 16 pallets. If one space were left open, the items or squares could be shifted internally by the AS/RS system to access any other item in the storeroom. However, the expected response time to obtain any randomly selected pallet could be too great to adequately support forces ashore in a combat environment. Alternatively, a storeroom could be packed slightly less dense, in other words with some of the items removed, so items could be quickly shifted or moved to other locations to retrieve any randomly selected pallet.

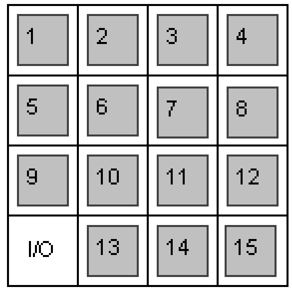

Figure 3 Very Dense 4 by 4 Storeroom Containing 15 Pallets

2. Purpose

The purpose of this thesis is to analyze the dynamic relationship between storage density, the configuration of pallets in storage, how pallets are retrieved, and the expected response times to retrieve pallets. The primary measure of effectiveness is the expected retrieval time of a storage system.

We "trade" small amounts of density for improved response times by constructing storeroom configurations that provide higher levels of accessibility. Since MPF(F) is likely to operate over-the-horizon with extended lines of supply and communication, we hypothesize that MPF(F) must be able to respond quickly when directly supporting forces ashore. The objective is to analyze and quantify the trade-off between storage density and mean retrieval time in a dynamic environment for a variety of different storage densities and configurations in notional MPF(F) storerooms. In addition, we examine two demand conditions and two different retrieval rules to determine how each storage configuration responds to a stream of randomly selected pallets over time in the notional storeroom.

Some of the questions we examine in this thesis include:

- What storeroom pallet configurations for different levels of access provide the best mean retrieval times? What do they look like (i.e. how are the pallets arranged)?
- What are the densities of the best performing storerooms?
- Are there retrieval rules that allow different storeroom configurations to better respond to retrieval requests? Under different demand conditions?
- Can we quantify the differences between the different retrieval rules?
- Do storerooms with greater accessibility equate to lower retrieval times?

Our results suggest that small square or near square storage configurations provide the best mean retrieval times for each accessibility level examined in this thesis. In addition, a simple retrieval rule can significantly reduce mean retrieval time under certain demand conditions especially for storage configurations with greater densities (i.e. lower levels of accessibility). These findings indicate that storage configurations with storage densities between 70% and 85% provide greater levels of sustainment and acceptable mean retrieval times and help achieve a balance between the storage density and mean retrieval time tradeoff than do storage densities outside this range.

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II. MODEL AND SCENARIO DESCRIPTIONS

A. OVERVIEW

1. Very High Density Storage Systems

A *Very High Density* (VHD) storage system is characterized by frequently having to move items in a storage area to gain access to a desired item. [Ref 26] The key characteristic of VHD storage system is increased densities but as a consequence less accessibility and higher response times. MPF(F) requires VHD storage systems in order to fulfill its role as the primary provider of MEB supplies and equipment and serve as the key distribution node of the future sea base. We explore a large variety of VHD storage configurations in this thesis by creating a conceptual model of the storage systems using Java and utilizing a simulation model, also created in Java, to capture each storage systems mean retrieval time under differing conditions.

2. Conceptual Model

The Storeroom model is a conceptual model that represents a notional MPF(F) VHD storeroom. This static model is used to determine the configuration of pallets in the storeroom based on three key variables (length, width, and depth of storage) and allows us to determine the density of a given configuration.

3. Simulation Model

The Selective Offload Capability Simulation or SOCS was created as a means to collect data for varying conceptual storeroom models and densities and their expected retrieval times for two different demand assumptions and two different retrieval rules. SOCS attempts to realistically model how an AS/RS would retrieve pallets from a storeroom. For example, SOCS simulates each configuration or Storeroom model in an AS/RS environment by selecting a pallet for retrieval, repositioning any pallets that block access to the selected pallet, retrieving the selected pallet, and then returning the pallets to locations in the storeroom. This is done repeatedly to simulate each storage system over time.

4. Assumptions

Constructing a model that incorporates all aspects of any AS/RS or foresees every situation is not only unachievable but also undesirable. Therefore, both the conceptual

Storeroom model and SOCS make certain assumptions that allow us to model and analyze an extremely complex system. The conceptual and simulation models both make the assumption that a future AS/RS system will be utilized in many of the stowage holds onboard future sea base platforms. We assume that the basic unit of storage is a pallet that is square by design. Therefore, the illustrations of all storeroom configurations in this thesis display square pallet locations and square pallets. In addition, we assume that our storerooms are free of shipboard like obstructions or support structures that are common throughout any ship. This assumption serves to simplify the model and provides a common means by which to compare designs and mean retrieval times.

We also assume our storage systems are *non-depleting* systems, meaning systems that case pick items from the pallet and then return the pallet back to the storeroom. In this type of system, the density of the storeroom remains constant. A non-depleting storage system like this on a future sea base will typically hold maintenance or supplies supporting forces ashore. Since the logistics functions and the supplies are held on the sea base, certain items will need to be case picked from their storage locations for further transfer from the sea base to the landing force.

A *depleting* storage system is a system that pulls pallets from a storeroom but doesn't return the pallet. In this instance, the density of the storeroom decreases as pallets are retrieved. Because the unit of issue is a pallet, a depleting storage system is commonly associated with high volume items like MRE's and ammunition or could be associated with combat logistics force ships that hold material for further transfer to other ships. Therefore the ability to get to any randomly selected pallet is not necessary. For items such as ordnance or MRE's (i.e. high volume, high demand), it makes sense to store these items in a very dense manner or with multiple pallets per stock picking unit (SKU). We do not examine depleting storage systems in our work.

5. Terms and Definitions

The following provides some definitions of the primary terms utilized in thesis and their meaning within the context of storage systems and configurations. Figure 4 illustrates the terms described below.

- An <u>*m* by *n*, *k-deep* storage system</u> is any AS/RS system that contains *m* rows and *n* columns. The variable *k* is directly related to the accessibility or physical access of any particular pallet in the *m* by *n* storage system and is referred to as the accessibility constant in this thesis. In a *k-deep* system, any item can be retrieved without moving more than *k* - 1 pallets. Figure 4 illustrates a *single-access* (*k* = 1) system, in which every item is immediately accessible and can be retrieved without having to move any other item. Figure 5 illustrates a 4-deep storage system in which every item can be retrieved without having to move more than three other pallets.

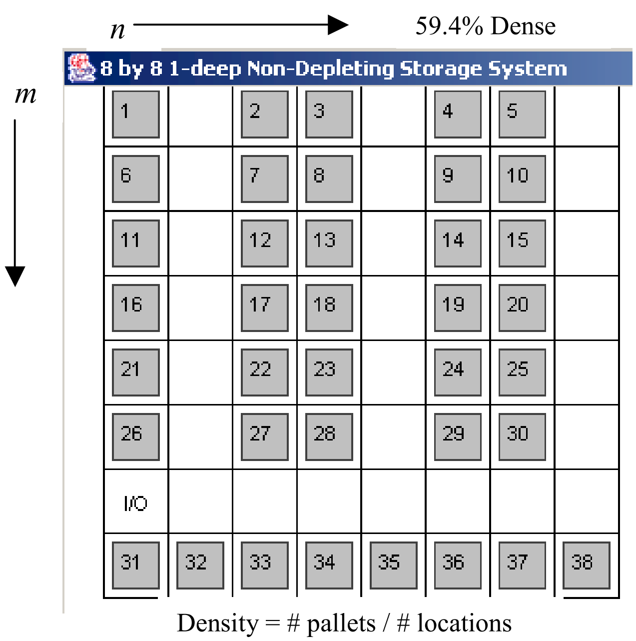


Figure 4 8 by 8, 1-Deep Storage System

- A <u>location</u> is any square in the *m x n* storage system.
- A <u>pallet</u> occupies a location. We assume the pallet is a storage container in an AS/RS system and may contain many different types of supplies.
- The Input/Output (I/O) point is the location to which pallets are retrieved.
- The <u>density of the storeroom</u> is the ratio of pallets to the number of pallet locations in an *m x n* storage configuration. Storeroom densities range from 0 to 1 since a storeroom can hold no more than <u>*m* x *n*</u> pallets.

- The theoretical mean retrieval time assumes every pallet, after selection, is returned to the location it came from and that every pallet has an equally likely chance of being selected. This is the minimum time for a particular storage system to retrieve pallets over the long term (i.e. a steady state measure) under these assumptions. This value is calculated by dividing the sum of the process times by the number of pallets in the storeroom.

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i, X_i > 0 \text{ for } \forall_i$$

$X_i =$ processing time of the ith pallet

- The maximum process time is the maximum X_i, and is normally associated with the pallet located in one of the three corners farthest from the I/O point. The minimum process time is normally associated with the two pallets located adjacent the I/O point. Figure 5 provides an illustration of the pallet with the maximum process time for that configuration and the pallets with the minimum process times. Lighter shading indicates pallets with lower process times and darker pallets indicate those with higher process times.

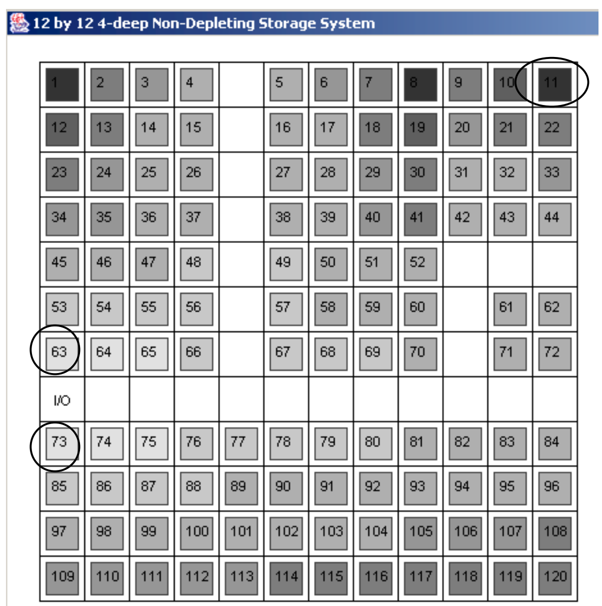


Figure 5 Process Time Shading for a 12 x 12, 5-Deep System

B. SIMULATION METHODOLOGY OVERVIEW

The first problem is to determine how densely and in what configuration a notional MPF(F) storeroom can be packed while still providing adequate mean response times. A second problem relates to the dynamic nature of the storeroom as streams of retrieval requests arrive for any randomly selected pallet in the storeroom. To gain insight into this relationship, we utilized the Storeroom Model and SOCS. An overview of the methodology used to create storerooms of various sizes, simulate retrieval requests, the movement of pallets, methods of retrieval, and differing demand to capture the mean retrieval times is provided.

First, we choose the variables m, n, and k. For this thesis, we vary m from 4 to 40, n from 4 to 40, and k from 1 to 5. Therefore, the smallest configuration is a system that is 4 by 4, 1-deep, while the largest configuration is 40 by 40, 5-deep.

The Storeroom model utilizes a packing algorithm that packs an m x n grid with pallets while maintaining k-deep access and then selects an Input/Output point. The model then determines the retrieval path to the I/O point from every location in the storeroom. We are examining non-depleting storage systems so the configuration of the storeroom does not change as pallets are retrieved. This allowed us to pre-calculate all of the retrieval paths. A pallet can then be moved to any location in the storeroom and based on that location its retrieval path is known and the total process time can be calculated.

The SOCS model analyzes two different retrieval rules under two different demand assumptions for each of the m by n, k-deep storage systems produced by the packing algorithm. For each combination of retrieval rule and demand condition, SOCS simulates streams of retrieval requests to randomly select individual pallets in the storeroom for retrieval. This procedure is replicated 50 times and the mean retrieval time captured for each storage system for later comparison and analysis.

The following provides the general methodology. Each bullet is discussed in greater detail in the next section.

Build a Storeroom

- Choose values of m, n, k and pack an m x n grid with pallets
- Select the Input/Output (I/O) point
- Determine the retrieval paths to the I/O point from every location in the storeroom

Simulate the Storeroom in an AS/RS Environment

- Simulate retrieval requests for individual pallets (i.e. select, retrieve, select, retrieve, etc.) under four scenarios
- Replicate the process
- Capture the retrieval process times of each pallet and calculate the mean retrieval time of that system for each scenario

Analyze the output

C. STOREROOM MODEL

1. Choosing *m*, *n*, and *k*

The Storeroom model incorporates an efficient packing algorithm called Fill-And-Rotate (Appendix A). [Ref 26] The packing algorithm is based on the concept of a k-deep system. Given an m x n grid, the algorithm produces a storage system design while maintaining k-deep access. The algorithm assumes that $n \geq m$ and $k < (m-1)/2$. Since m is varied from 4 to 40, n from 4 to 40, and k from 1 to 5, the algorithm produces 2,825 different storage systems as displayed in the Table 1. Appendix D provides many examples of the different pallet configurations produced by the packing algorithm for a variety of storeroom sizes.

Accessibility constant (*k*)	**Smallest *m***	**Configurations**
1	4	703
2	6	630
3	8	561
4	10	496
5	12	435
Total		2825

Table 1 Number of Configurations Produced by the Packing Algorithm by Varying *m* from 4 to 40, *n* from 4 to 40, and *k* from 1 to 5.

Based on the values chosen, the algorithm packs an m x n grid maintaining k-deep access as depicted in Figure 6 and Figure 7 below. The gray-numbered squares are pallets and are numbered to illustrate the total number of pallets in any given storage system. The white squares are aisles or open locations.

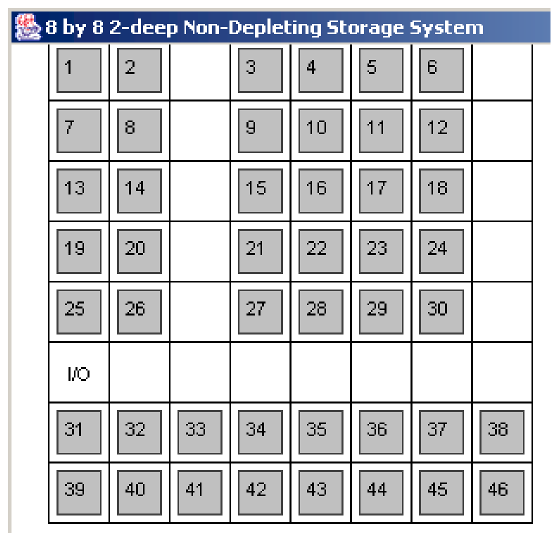


Figure 6 8 by 8, 2-Deep System

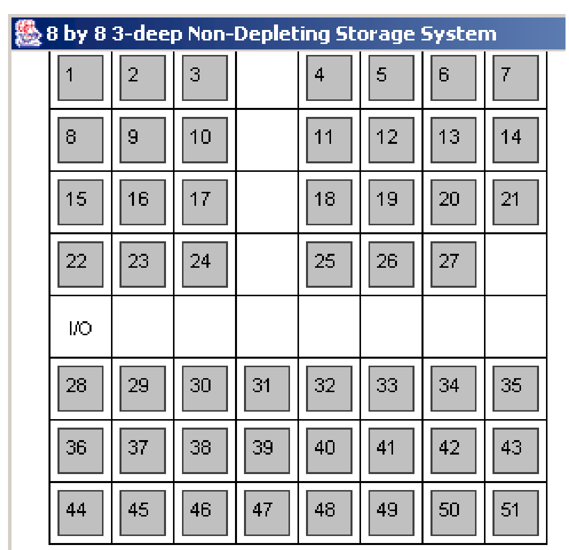


Figure 7 8 by 8, 3-Deep System

The 8 by 8, 3-deep design provides a good example of how any item in this design can be retrieved without having to move more than two items. In both examples, an additional pallet cannot be placed anywhere in the storeroom configuration with violating the *k*-deep access requirement. Placing a pallet in any white square in either of the Figures above violates this condition. Although an optimality proof has not been completed to determine if the packing algorithm is in fact optimal, we have not found a storeroom configuration produced by the algorithm where an additional pallet could be added that would increase the density of the storeroom and not violate the *k*-deep condition.

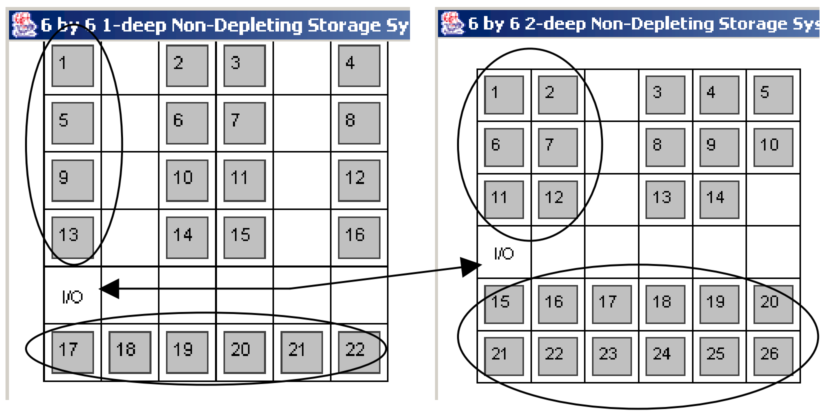
2. Choosing an Input/Output Point

Once the model produces a configuration based on the packing algorithm, an input/output (I/O) point is chosen. The algorithm produces designs with a minimum of three I/O points for every design. Appendices C and D illustrate several storage systems of varying shapes and densities that display the different I/O point possibilities.

Future storerooms on a sea base could in fact have single or multiple I/O points for any storeroom depending on many design factors and other requirements. One of the strengths of the packing algorithm is that it not only allows for many different options from an engineering design standpoint on future sea base platforms but allows the decision makers varying levels of access to any item in storage. We chose to model the storeroom configurations utilizing a single I/O point, specifically the I/O point location on the left side of every storage system.

Since each configuration has multiple I/O points, we examined a small sample of eight storage systems to determine the I/O point that produced the lowest theoretical mean retrieval time for that configuration. The I/O point located on the left side of the configuration at the $(m-k)^{th}$ aisle location produced the lowest theoretical mean retrieval time for all eight configurations. In addition, this particular location was chosen because of the way in which the algorithm packs every m x n grid with pallets. Each and every design begins with a row of k items along the bottom of the configuration followed by a single open aisle that runs straight across the entire storeroom. Two such illustrations are provided in Figure 8 below. In both cases, the I/O is in the same $(m-k)^{th}$ aisle location on the left side of the storeroom. All 2,825 storage systems examined share this common I/O point, which allows us to make comparisons of the mean retrieval times. Choosing an I/O point that wasn't shared by all 2,825 storage systems would have limited the number of comparisons that could have been made.

$k = 1$ $\qquad\qquad\qquad\qquad$ $k = 2$



The I/O point is located at the $(m-k)^{th}$ aisle location from the base.

Figure 8 Input/Output Point Depiction for a 6 x 6, 1- and 2-Deep System

3. Retrieving a Pallet

After the storeroom configuration is established with *m x n* possible locations and some number of pallets, the storeroom model determines the path each pallet would take when selected for retrieval from its current location to the I/O point. The pallets do not actually retain any knowledge of how to get to the I/O point. Each location in the storeroom, being a physical space, retains knowledge of how any pallet residing in that location would exit to the I/O point. The path is determined by first finding the closest aisle. The closest aisle is defined as the fewest number of locations between a location that stores a pallet and the nearest aisle location. A pallet can move in only one of four directions (i.e. North, South, East, or West). If two different aisles are the same number of spaces from the location, the aisle that is nearest the I/O point, based on a straight-line distance calculation, is chosen. Figure 9 illustrates how the model would determine the closest aisle location and the path pallet 16 would take to the I/O point. The first and second sets of nearest neighbors checked for the closest aisle (i.e. pallets 7, 17, 25, and

15; and pallets 18, 34, and 14 respectively) do not include an aisle location. The third set of nearest neighbors includes pallet 43 and an aisle location. The algorithm then selects the aisle location and will allow pallet 16 to proceed down the aisle to the I/O point after any pallets that block access to it are repositioned.

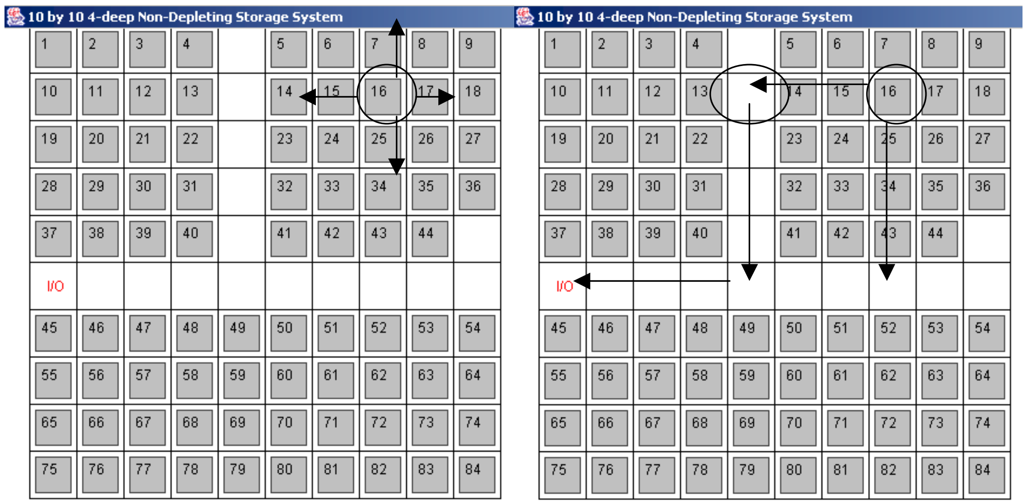


Figure 9 Determination of the Closest Aisle for a 10 x 10, 4-Deep System

In Figure 9, two pallets block pallet 16's path to the I/O point. To retrieve pallet 16, pallets 14 and 15 must be repositioned in the open aisle locations that do not impede pallet 16's path to the I/O point. We use very simple rules to determine where to reposition the blocking pallets. Pallet 14, adjacent to the aisle, would be repositioned first. Pallet 14 moves along its path to the I/O but does not actually proceed all the way to the I/O point. Instead it searches for the first unoccupied location not along its exit path. If there are additional unoccupied locations beyond the initial unoccupied location, pallet 14 proceeds to the next unoccupied location but moves no more than the total number of pallets that need to be repositioned. In this example, pallet 14 moves no more than two spaces off its exit path since only two pallets required repositioning.

Figure 10 provides an illustration of how pallets 14 and 15 would be repositioned to provide access to pallet 16 for retrieval. In this example, the closest aisle was only two locations away from the selected pallet. An alternate retrieval path does exist; however, it requires moving three pallets, pallets 25, 34, and 43, which would take longer than the path the algorithm chose and executed.

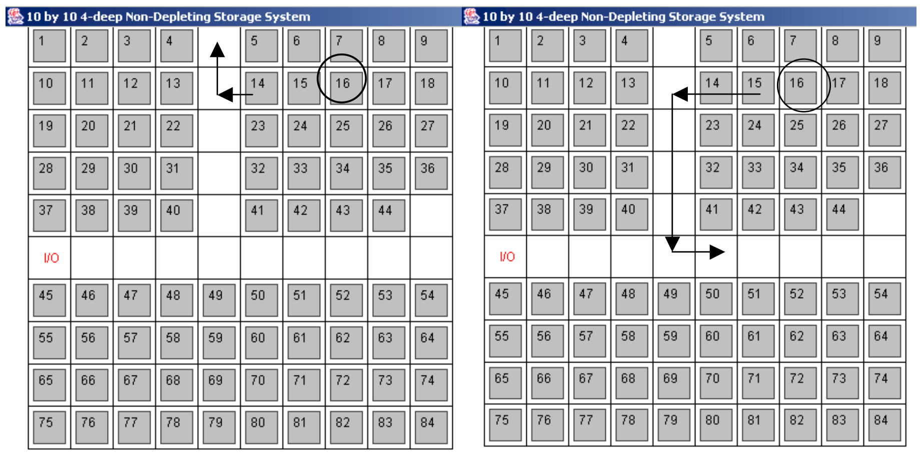


Figure 10 Pallet Repositioning in a 10 x 10, 4 Deep System

D. SELECTIVE OFFLOAD CAPABILITY SIMULATION (SOCS)

The key areas in SOCS include the implementation of streams of retrieval requests over time, repeated replications to estimate long term or steady state results, the use of common random numbers across each scenario and simulation run, and the simulation of all possible combinations of two retrieval rules and two demand conditions.

1. Retrieval Rules

a. Naïve Retrieval Rule

The first retrieval rule pulls pallets for offload and the pallet is returned to the same location in the storeroom from which it was retrieved. The pallets are not only returned to their original location in the storage system but the configuration of pallets is also maintained as originally produced by the packing algorithm. In other words, the conceptual Storeroom model maintains its shape and density. This is the *naïve retrieval rule*.

b. Move-to-Front Retrieval Rule

The second retrieval rule retrieves pallets for offload but instead of returning the pallet to the same location in the storeroom, it is returned to the closest location adjacent to an aisle if it doesn't already occupy one. The overall pallet configuration is again maintained but retrieved pallets are not always returned to their original location. This is the *move-to-front (MTF) retrieval rule*. The intent of this rule is to move the most recent selection to the closest aisle location if the item doesn't already occupy an aisle location. This ensures that the most recent selection is repositioned so no other pallet blocks its access to the I/O point thereby decreasing the time it takes to retrieve that pallet.

We note that there is no additional cost in executing the move-to-front retrieval rule than the naïve retrieval rule. To achieve this result, we ignore the cost of unloaded travel (i.e. the time a payload carrier travels empty from one location to another) and factor in only the cost of loaded travel (i.e. the time the payload carrier is either retrieving or repositioning a pallet). The amount of unloaded travel is small in comparison to the amount of loaded travel in very dense storerooms and has little impact on the overall retrieval cost. Therefore, the total time to process any pallet in a storeroom is based on two primary factors; the distance the pallet has to travel to the I/O point and how many pallets block access to it. Figure 11, Figure 12, and Figure 13 illustrate the MTF concept and how the cost (in terms of repositioning moves) of executing the retrieval rule is the same as the naïve retrieval rule.

For example, if pallet 11 is selected, pallets 22, 33, 44, and 55 must be repositioned to access pallet 11. The blocking pallets are moved to the four closest empty aisle locations that do not impede the path of the selected pallet. After pallet 11 is retrieved, pallets 22, 33, 44, and 55 are relocated before pallet 11 is returned to a new location adjacent an aisle. Pallets 22, 33, 44, and 55 are relocated to exactly one pallet location away from their previous location as displayed in Figure 13. The total cost of moving each of the four pallets one additional location is four. However, pallet 11 only needed to moved to the closest location directly adjacent an aisle that was previously occupied by pallet 55. This results in a savings of four since Pallet 11's return path is exactly four grid spaces shorter than its exit path (13 grid spaces vs. 17 grid spaces) as displayed in Figure 13. The net cost of implementing the move-to-front retrieval rule is zero

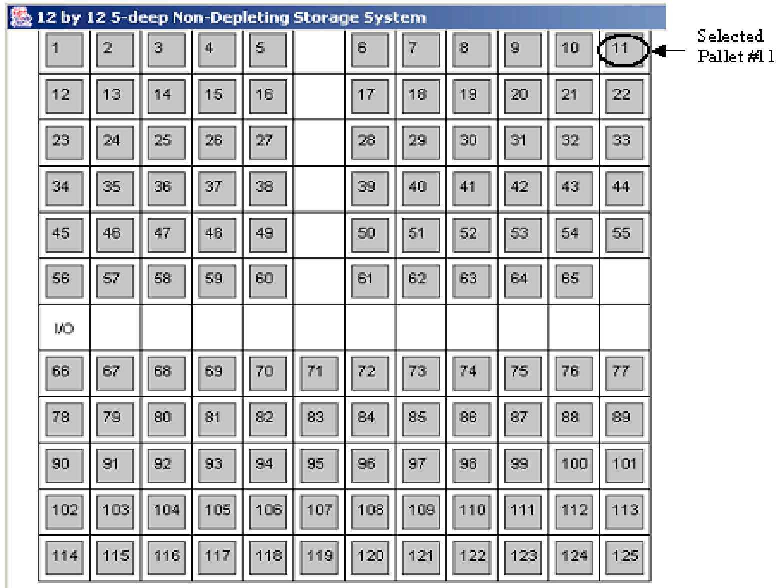


Figure 11 Move-to-Front Retrieval Rule Illustration where Pallet 11 Selected for Retrieval in a 12 x 12, 5 –Deep System

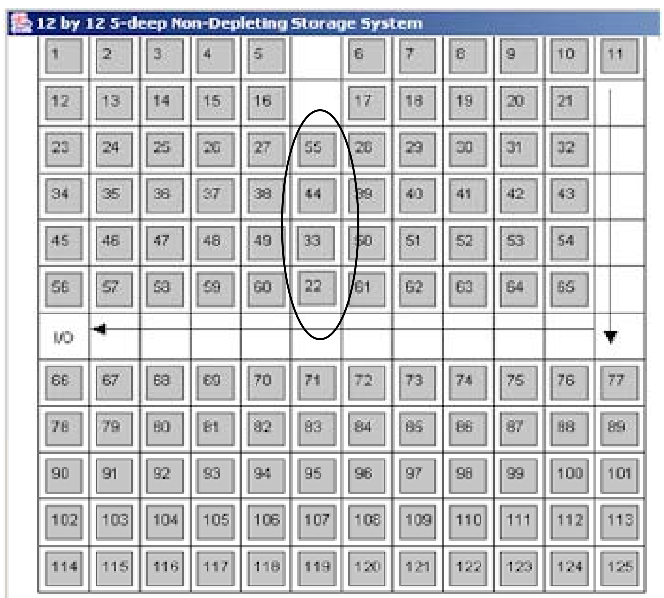


Figure 12 Move-to-Front Retrieval Rule Illustration Demonstrating How and Where Pallets that Block Access to Pallet 11 are Repositioned in a 12 x 12, 5-Deep System

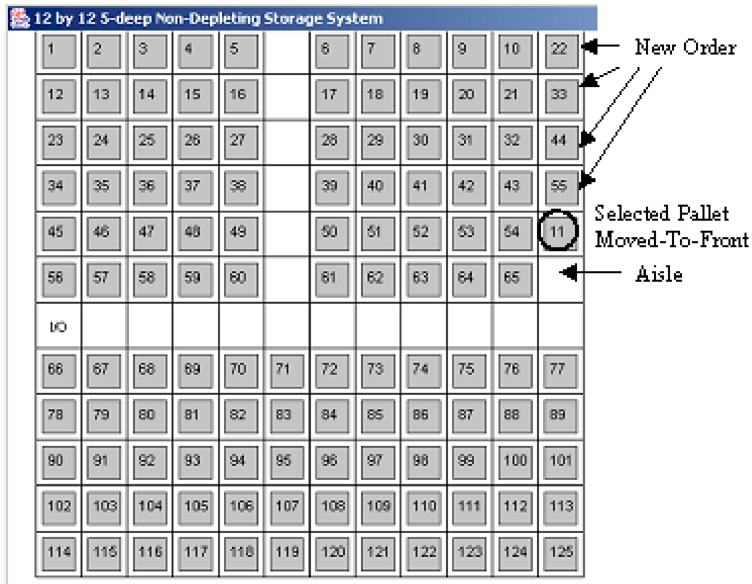


Figure 13 Move-to-Front Retrieval Rule Illustration Demonstrating How the 12 x 12, 5-Deep System is Reconfigured Following Pallet 11's Selection

2. Demand Conditions

Two demand conditions are utilized when analyzing the different storage systems. One assumes a homogenous distribution of demand and a second that assumes two pools of items with differing demands. The first demand condition assumes a homogeneous distribution of the probability of selection among all pallets in the storage system (i.e. no one pallet is more likely to be selected than any other). This type of demand distribution we call *uniform demand*. The second demand condition assumes 20% of the items in inventory experience 80% of the demand and 80% of the items experience 20% of the demand [Ref 15]. This type of demand distribution we call *Pareto's (80/20) demand*.

3. Scenario Summary

Each scenario involves a combination of one of two retrieval rules and one of two demand conditions for a total of four scenarios as displayed in Table 2. Storage system designers can choose the type of retrieval rule to operate their system but cannot choose a demand profile. Demand is based on many variables that change from day to day.

Retrieval Rule	Uniform Demand	Pareto (80/20) Demand
Naïve	**Naïve-Uniform**	**Naïve-Pareto**
Move to Front (MTF)	**MTF-Uniform**	**MTF-Pareto**

Table 2 Summary of the Four Scenarios that Simulate the Different Combinations of Demand and Retrieval Rule

4. Storeroom Travel and Pick Time Characteristics

Process times are associated with every pallet location in the storeroom and those process times are made up of both *travel* and *pick times*. The *travel time* is the time it takes the AS/RS system to move a pallet from one square grid to the next square grid as illustrated in Figure 14 below. The *total travel time* is the total time to retrieve the pallet, move any pallets that block access to the exit, and then return the selected pallet and any repositioned pallets to their assigned locations.

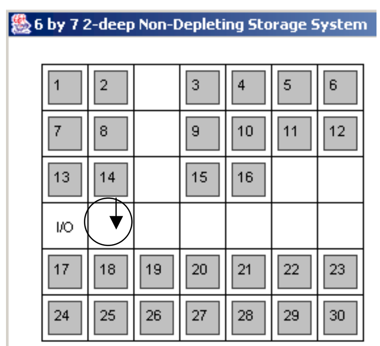


Figure 14 Travel Time Depiction for a 6 x 7, 2-Deep System

The time for an AS/RS system to physically pick-up the pallets, place them down, pick them back up again, and put them back down when the system is reset is referred to the *pick time*. The *total pick time* is the total time to pick up and place back down any pallets that block access to the exit, pick up and place back down the selected pallet for retrieval, and then do the same when returning pallets to their locations.

For the purposes of estimation and analysis, we utilized a travel time of seven seconds and a pick time of 18 seconds. The times are based on estimates from the NAVSTORS system. [Ref 16]

5. Streams of Retrieval Requests

One of our objectives is to determine which m,n,k storage systems tend to produce lower mean retrieval times. To adequately capture the mean retrieval time for each storage system under the demand conditions and retrieval rules, each system is fed a similar ratio of retrieval requests to pallets. The ratio of retrieval requests to pallets utilized for each system was 20 retrieval requests per pallet in the storeroom. For example, a 12 by 12, 5-deep storage system contains 125 pallets and a 6 x 6, 2-deep storage system contains just 26 pallets. SOCS simulates 2,500 retrieval requests for the 12 by 12, 5-deep system and 520 retrieval requests for the 6 by 6, 2-deep system. This ratio of retrieval requests per pallet is maintained for all m,n,k systems across all four scenarios. It should be noted that the ratio of retrieval requests to pallets was based on some experimentation with ratios ranging from five to thirty. Utilizing a ratio of twenty retrieval requests per pallet was adequate to capture a single mean response time data point and reduce the variation between runs. There was little improvement by increasing the ratio for example to 30 requests per pallet.

6. Replications

Although each system is subject to a high volume of retrieval requests per simulation, that alone is not sufficient to ensure the mean retrieval time of each system is obtained. To do this, each m,n,k system with a ratio of 20 retrieval requests per pallet is replicated 50 times for each of the four scenarios. A total of 50 replications was chosen based the Central Limit Theorem to capture the mean retrieval times of each storage system in each scenario.

7. Use of Common Random Numbers

We compare two alternative retrieval rules (move-to-front vs. naïve) for each m,n,k system under two different demand assumptions. The goal is to ensure that differences in performance between the two retrieval rules under the two conditions is the result of the differences in how each system responds to individual retrieval requests and not to fluctuations in the experimental conditions. In simulations, the experimental conditions are the generated random variates that are used to drive a particular model through simulated time. [Ref 19, pp. 582-583] In SOCS, for instance, these are the pallets that are selected for retrieval. By ensuring that the same sequence of pallets is selected for retrieval for each of the four scenarios, we can be more confident that any differences in performance are due to the differences in the retrieval rules. This method is a variance-reduction technique utilizing common random numbers (CRN). Our goal is to determine if one of the alternative retrieval rules provide a lower expected mean retrieval time under the demand assumptions.

Typically simulations are run so the observations taken from each of the alternative configurations are independent of each other and are identically distributed. The random numbers are set-up in a way so X_{1j} and X_{2j} are completely independent so that the $COV(X_{1j}, X_{2j}) = 0$, where X_{ij} is the j^{th} output from system *i*. By utilizing common random numbers, we are able to induce positive correlation between X_{1j} and X_{2j} so that the $COV(X_{1j}, X_{2j}) > 0$. For instance, if we compare two different systems $(X_1 \text{ and } X_2)$, then the variance of their difference, $VAR(X_{1,} X_2)$, is equal to the $VAR(X_1) + VAR(X_2) - COV(X_1, X_2)$. [Ref 19, p. 240] If the two systems were independent, the covariance of X_1 and X_2 is equal to zero and has no effect on the result. On the other hand, if the two systems were dependent, a common problem in simulation experiments, the covariance could have a positive or negative effect on the variance depending on the relationship. By inducing a positive covariance, we gain a real benefit of reducing the variance of our estimator, in this case the mean retrieval time of each storage system. The reduced variance then leads to better confidence intervals and most likely a stronger declarative statement about the difference between two systems.

The set-up for each simulated system across each run was synchronized so the random numbers to begin replication one on the first configuration was the same for the next configuration. In addition, each subsequent replication of that system was synchronized with the replications of the next system. In other words, each of the alternative storage systems was subjected to identical experimental conditions so that any difference between the different systems is more easily detected.

8. Validation and Verification

A key step in building and implementing a simulation of any system is to determine if the model is an accurate representation of the systems being studied and performs as advertised. The Storeroom model and SOCS model together were designed to model how an AS/RS system might operate on a future naval ship. AS/RS systems are in operation today in many civilian-warehousing facilities. However, to date, no ASRS system has been installed on a naval ship and many of the systems proposed for ships are still under experimentation.

The Storeroom model is a good conceptual representation of a notional MPF(F) storeroom based on the packing algorithm. We verified this by checking a large sample of more than 100 configurations produced by the algorithm and comparing them against a separately coded implementation in the software package Mathematica. In addition, the Storeroom model is capable of producing a visual graph of the pallet configuration in the storeroom and more than 50 of those have been produced during this thesis. No errors have been found in the implementation of the algorithm.

The simulation model, SOCS, was built and debugged in steps. Since the model retrieves or repositions one pallet at a time, the model was traced based on the action taken to each pallet one at a time in a discrete manner. For example, we verified that the model produced correct exit paths and process times by literally computing many of the alternatives first by hand and then comparing the model against the calculations. The implementation of common random numbers was verified by checking various correlation plots and correlation tables for numerous simulations for all four scenarios to ensure positive correlation was attained as expected. In addition, the scenarios themselves provided a form of verification. By comparing the means and variances of scenarios Naïve-Uniform to MTF-Uniform and Naïve-Pareto to MTF-Pareto for single access storage systems (i.e. an accessibility constant of one) in SOCS, we find that there is no difference between the two. In a single access storage system, the move-to-front (MTF) retrieval rule provides no benefit since every pallet in the storeroom is already in front and adjacent an aisle location. Therefore, by design, scenarios Naïve-Uniform and MTF-Uniform should have equal means and variances for every single access m x n storage system and scenarios Naïve-Pareto and MTF-Pareto should have equal means and variances for every single access $m \times n$ storage system. An analysis of the results proved this to be true.

E. LIMITATION OF THE MOVEMENT ALGORITHM

One limitation of the Storeroom model is the method in which an exit path to the I/O point is determined. Figure 15 and Figure 16 illustrate two possible exit paths for the selected pallet, pallet 7, to exit to the I/O point. In Figure 15, when pallet 7 is selected for retrieval, pallets 8 and 9 are repositioned since they block access. These pallets are moved down the vertical aisle on the right hand side until they are clear of the selected pallets exit path and positioned in the first two open locations in the center vertical aisle indicated by the two stars in Figure 15.

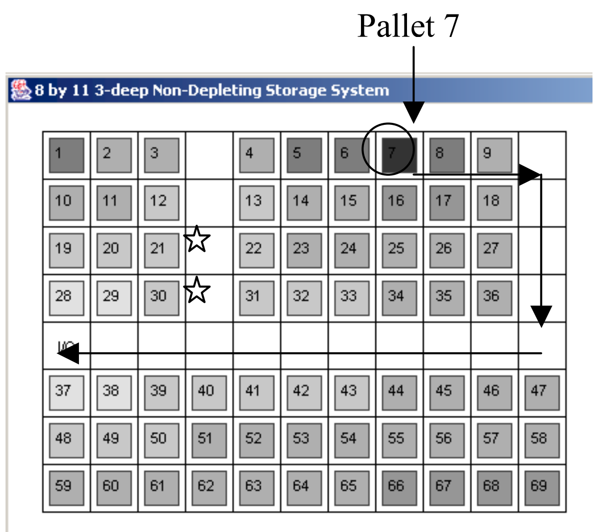


Figure 15 Display of 8 by 11 Pallet Retrieval

An alternative exit path for pallet 7 is displayed in Figure 16. This exit path requires pallets 16, 25, and 34 to be repositioned. Although one additional pallet requires repositioning, the three pallets need only to move a total of four spaces (one-way) to be repositioned and another four spaces to be placed back in their original locations. A total of eight moves per pallet or 24 repositioning moves are required to retrieve pallet 7. When pallets 8 and 9 are repositioned, it requires 14 moves (one-way) per pallet for a total of 28 moves per pallet or 56 repositioning moves or more than twice as much as the alternate method.

This demonstrates that the movement algorithm created by the author is certainly not optimal. The movement algorithm, however, does produce the shortest exit path to the I/O point for the majority of the pallets in any given configuration. We believe the effect of this limitation on our results to be negligible.

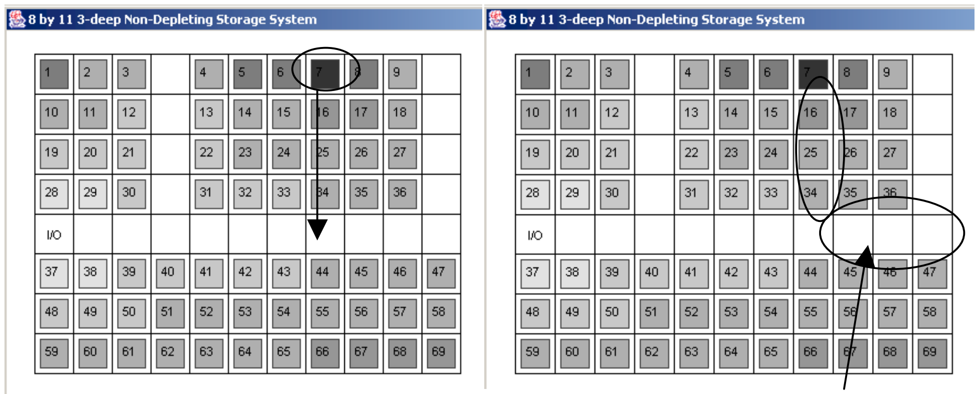


Figure 16 Illustration of a Better Pallet Repositioning Move

F. METHOD OF ANALYSIS

Classical statistical techniques typically rely on the assumptions that the data are independent and identically distributed with normal means. One of the problems in analyzing the output from simulations is that these assumptions are rarely met. The implementation and use of common random numbers in simulations results in data that is usually positively correlated by design. In addition, if fewer simulation replications are conducted because of the length of time to run each simulation and generate data, the assumption of normality can be hard to justify.

1. Screening, Selection, and Multiple Comparison Methods

Our objective is to compare a large number of alternative storage systems to determine if any one of a subset of systems performs better over time with regard to mean retrieval time. Ranking, selection, and multiple comparison methods are the typical methods utilized to compare alternative systems via simulation. The goal of these methods is to determine the best system. The ranking and selection procedures can also be utilized to find smaller subsets of a large number of competing systems if there is little or no difference between systems.

We used common random numbers (CRN) to reduce the variance of the estimates when comparing alternative systems. Implementing CRN however, requires use of procedures that do not require independent samples across the storage systems to select the best systems. In fact, use of common random number complicates the statistical analyses of the SOCS output since the assumption of independence cannot be supported. However, *multiple comparison procedures* (MCP), such as one developed by Nelson and Matejcik (1995), are easily adaptable, and statistically valid when analyzing computer simulation output. [Ref 21, p. 142] The procedure, called Nelson, Matejcik and Multiple Comparisons with the Best or referred to in the literature as NM + MCB, exploits the use of common random numbers to reduce the total number of observations. In addition, the NM + MCB procedure is robust to departures from the conditions under which the simulations were run. [Ref 21, p. 140] A complete description of the notation and NM + MCB procedure can be found in Appendix B.

Multiple Comparison Procedures, in general, determine the best storage system by forming simultaneous confidence intervals on the parameters $\{u_i - \min_j u_j \mid i \neq j\}$ and explicitly account for the joint overall error in making such statements with multiple intervals. The simultaneous confidence intervals are called *multiple comparisons with the best* (*MCB*) and bound the difference between the expected performance of each storage system and the best of the others. [Ref 21, p. 141] The intervals provide quantitative information as to how much better the best system really is and how close is the next best system.

The widths of the MCB confidence intervals correspond to an indifference-zone. This difference amount is a user specified positive value that provides a better guarantee that we did in fact select the best system. The objective behind an indifference zone is to preclude running unnecessary simulations or additional replications to resolve differences less than the indifference amount. We used an indifference zone of ten seconds when comparing retrieval rules between systems of the same size and accessibility and fifteen seconds when making direct comparisons of storage systems of different sizes and accessibility. The indifference zone is measured in seconds since the pick and travel times used to estimate pallet movement was also measured in seconds.

We used a larger indifference zone for comparisons of different systems because of the expected variation between systems of differing size, accessibility, and pallet configuration. A larger indifference zone also provides greater assurance that any individual selection is the best system or a selection of a subset at least contains the best system. In addition, a larger indifference zone makes it more likely that an MCB procedure selects a subset rather than an individual system and therefore provides decision makers with greater flexibility when planning storage systems especially for shipboard use.

The confidence intervals formed by the NM + MCB procedure are constrained to contain zero (i.e. zero is each confidence intervals left end-point or right end-point or can be strictly within). If the confidence interval for $\{u_i - \min_j u_j \mid i \neq j\}$ contains zero as its right end-point, then that storage system is declared to be the best because we are $(1-\alpha)\%$ confident that the design has the lowest mean retrieval time. If zero is the left end-point of the interval, then there is at least one other system that is better than that design. If the confidence interval contains zero between the left and right bounds, then that storage systems mean retrieval time is less than the indifference amount higher than the system with the lowest mean retrieval time.

The NM + MCB procedure assumes unknown and unequal variances, positive correlation, and normal observations between each of the scenarios. However, the procedure has been shown to be quite robust to departures from the assumptions and unlike other MCP's is designed to exploit the use of CRN to reduce the total observations required to make a correct selection. [Ref 22, p.163] The NM + MCB procedure is also robust enough that even moderate departures from normality do not pose a problem. [Ref 22, p. 164]

Another assumption is that the use of CRN does in fact induce a positive correlation that results in a reduction in the variance of our estimator, the mean retrieval time. However, there is no general proof that CRN does in practice work as intended. [Ref 19, 584] To ensure that the intended results were achieved, streams of observations for some of the systems under each scenario were tested for positive correlation. In most of the cases analyzed, there was in fact positive correlation between the sets of observations and as a result a net reduction in the variance of the estimator, mean retrieval time. However, there were a few instances of negative correlation, although small. The presence of negative correlation has no effect on the results because of the robust procedure utilized to analyze the results. The NM + MCB procedure is robust against departures from CRN backfires because it utilizes the pooled variance estimator as the primary means of conducting the MCP. [Ref 23, p 232]

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III. MODEL FINDINGS AND RESULTS

This chapter provides a synopsis of the results and general findings of the Storeroom model and the Selective Offload Capability Simulation. For each of four scenarios, we examined 2,825 storage configurations. The objective was to highlight the tradeoffs between storage density, storage size, and mean retrieval time of different m x n combinations and determine if the move-to-front retrieval rule provided any improvement in the mean retrieval time over the naïve retrieval rule.

We used the mean retrieval time (measured in seconds) to quantitatively compare each retrieval rule and various m, n, k storage systems. A lower mean retrieval time for any particular storage system implies that the system can retrieve any randomly selected pallet over time better than an alternate system.

A. SOCS SCENARIO RESULTS

1. Overview

We ran the Naïve-Uniform scenario first in SOCs and analyzed the outputs prior to running the remaining scenarios. This was done to determine what the expected retrieval time was under the most basic assumptions, which we assume to be uniform demand and a naïve retrieval rule. It also provided a way to ensure the simulation was running correctly before generating 400,000 additional data points. Figure 17 provides a plot of the 2,825 observations, from the Naïve-Uniform scenario.

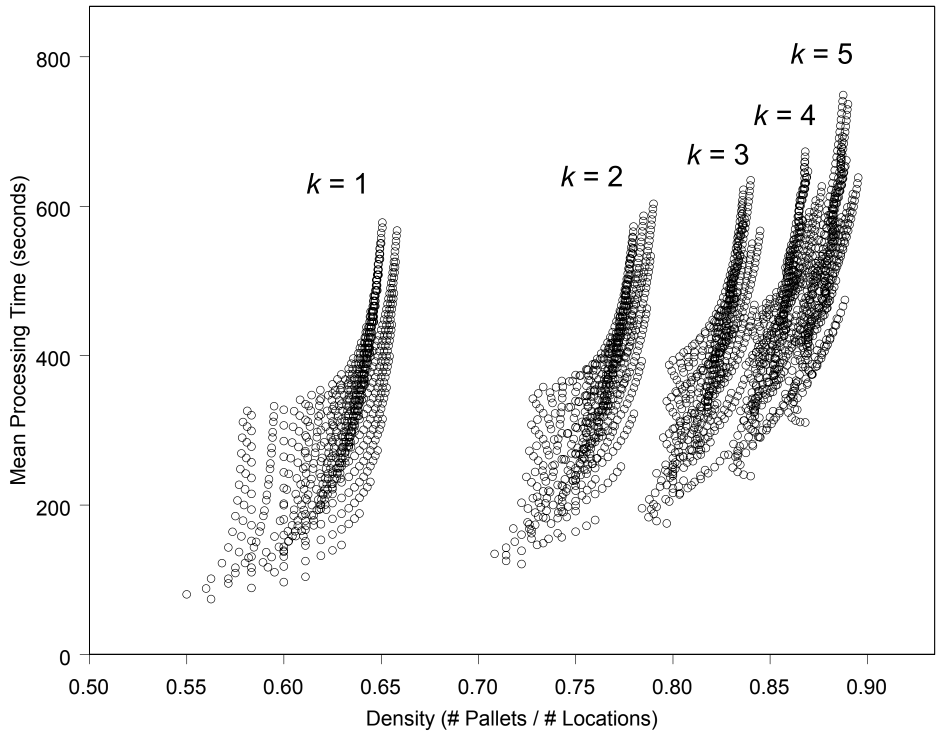

Figure 17 Plot of Mean Retrieval Time vs. Storeroom Density of all 2,825 Storage Systems Examined in the Naïve-Uniform Scenario

The density of any particular system is directly related to the accessibility of items in storage, or *k*. In Figure 17, as the value of *k* is increased from one to five, the storage density jumps substantially between $k = 1$ and $k = 2$, with smaller and smaller increases between each increasing level of *k*. Each of the data point groupings represents a different level of *k*. As the size of the system is increased (increasing *m* or *n*) for each level of *k*, the mean retrieval time increases rapidly while the storage density approaches an asymptote that is directly related to *k*. The asymptote for each level of *k* is equal to $2k/2k+1$. [Ref 26] For example, when $k = 1$, the result is approximately 67%. This agrees with the observations plotted in Figure 17 where the first grouping of points rise very rapidly near the density of 67%.

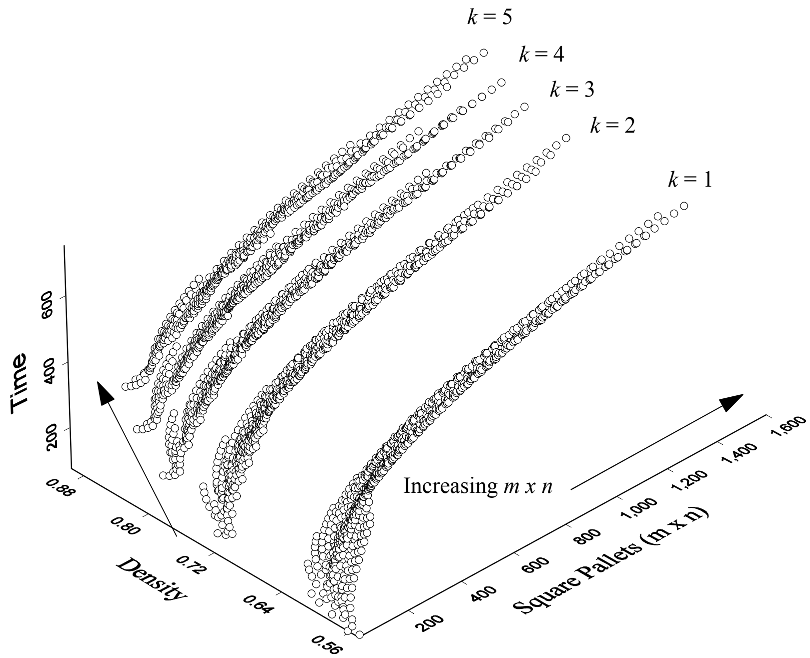

Figure 18 Naïve-Uniform Scenario, Retrieval Time vs. Density vs. Square Pallets

Figure 18 illustrates the relationship between k, m x n, and the number of pallets stored (i.e. the density of the system). As k increases, the density of the storage system increases while the percentage increase from one k to the next (i.e. the space between each of the k bands in Figure 18) gets smaller. In addition, the lowest retrieval times associated with each k band also increase. The increase in mean retrieval time is primarily associated with the packing algorithm since it requires that $n \geq m$ *and* $m > 2k+1$ (i.e. the smallest k = 5 system is a 12 by 12 storage system which will have a higher retrieval time than the smallest k = 1 system a 4 by 4 storage system). Generally, if storage system X $(m_1 \text{ x } n_1)$ is larger than storage system Y $(m_2 \text{ x } n_2)$, X will have a higher mean retrieval time than Y for similar values of k, because pallets, on the whole, must travel farther to reach the I/O point.

Figure 18 also indicates that increasing m or n has a much greater effect on the mean retrieval time than does increasing k. As k nears five, the improvement in density is smaller and smaller while the increase in mean retrieval time is greater and greater.

Table 3 displays the average change in density and the average change in retrieval time as the accessibility constant is increased from one to five. These average values are based on the 435 *m* x *n* storage systems that are common for each accessibility constant examined.

First, we note how the storage density of the systems increases on average by 20%, as *k* is increased from one to two, while the mean retrieval time increases by only 5.68%. With each additional increase in the accessibility constant, the gain in density is smaller and smaller while the percentage change in retrieval time increases rapidly. The results suggest that an accessibility constant of two or three is best with storage densities that range from 70% to 85%. At these storage density levels, we achieve a better balance between how much we can store and the mean retrieval time.

Accessibility constant (*k*)	**Average Density**	**Percentage Change in Density**	**Percentage Change in Retrieval Time**
1	64.27%		
2	77.17%	20.09%	5.68%
3	82.71%	7.18%	7.73%
4	85.84%	3.79%	9.11%
5	87.83%	2.33%	10.01%

Table 3 A Comparison of the Average Percentage Change in Density to the Average Percentage Change in Retrieval Time of 435 Storage Systems in the Naïve-Uniform Scenario

2. Scenarios Naïve-Uniform and MTF-Uniform

We simulated the Naïve-Uniform and MTF-Uniform scenarios to determine if the move-to-front retrieval produced lower retrieval times than the naïve retrieval rule under uniform demand conditions. Utilizing the NM + MCB procedure, we formed the MCB confidence interval with an indifference parameter of 10 seconds and a probability of correct selection of 97.5% ($\alpha = .025$). No additional observations were required after the first stage of the procedure. We used a value of 2.32 for g_α based on $n_o = 50,\ k = 2,$ and $\alpha = .025.$ [Ref 25]

Table 4 provides a snapshot of just five of the 2,825 storage systems analyzed and their corresponding confidence intervals. For sake of clarity, a single confidence interval is displayed instead of two simultaneous confidence intervals for the same system for each scenario. The shaded values in Table 4 represent the lowest mean retrieval times for that particular storage system and corresponding scenario. The greatest difference between the mean retrieval time of any one of the 2,825 systems in the Naïve-Uniform and MTF-Uniform scenarios was 1.6 seconds, much lower than the indifference parameter of ten seconds. All of the confidence intervals include zero and therefore no system in the MTF-Uniform scenario performed any better than in the Naïve-Uniform scenario. As expected, the move-to-front retrieval rule does not provide any improvement in the expected retrieval time for any of the 2,825 systems analyzed under uniform demand conditions.

m	**n**	**k**	**Density**	**MTF-Uniform Retrieval Time (secs)**	**Naïve-Uniform Retrieval Time (secs)**	**Lower MCB**	**Upper MCB**
12	12	1	0.639	189.02	189.02	-10.00	10.00
12	12	2	0.743	204.09	204.28	-9.81	10.19
12	12	3	0.806	232.66	232.61	-9.95	10.05
12	12	4	0.833	265.37	265.13	-9.76	10.24
12	12	5	0.868	310.18	310.14	-9.96	10.04

Table 4 MCB Comparison, Scenario 1A vs. 2A

3. Scenarios Naïve-Pareto and MTF-Pareto

Under Pareto demand the results are different. Again utilizing the NM + MCB procedure, the MCB confidence interval was formed with an indifference parameter of 10 seconds and a probability of correct selection of 97.5% ($\alpha = .025$). No additional observations were required to be generated after the first stage of the procedure. A value of 2.32 for g_α was utilized based on $n_o = 50,\ k = 2,$ and $\alpha = .025.$

Table 5 provides a snapshot of the same 12 by 12 storage systems (one for each level of *k*) along with the confidence interval. The highlighted mean retrieval time indicates the scenario with the lower of the two means upon which the confidence interval was based utilizing the NM + MCB procedure.

m	***n***	***k***	**Density**	**MTF-Pareto Mean**	**MTF-Uniform Mean**	**Lower MCB**	**Upper MCB**
12	12	1	0.639	187.73	187.73	**-10.00**	**10.00**
12	12	2	0.743	188.13	203.45	5.32	25.32
12	12	3	0.806	196.2	232.12	25.92	45.92
12	12	4	0.833	199.15	265.83	56.68	76.68
12	12	5	0.868	210.47	306.34	85.87	105.87

Table 5 MCB Confidence Intervals Comparing the MTF Retrieval Rule to the Naïve Retrieval under Pareto Demand

The confidence intervals for all 703 single access systems included zero indicating that the move-to-front retrieval provided no improvement in mean retrieval time. Of the remaining 2,122 higher density storage systems analyzed (i.e. those with storage densities greater than 70% and k = 2, 3, 4, or 5), not one of the MCB confidence intervals included zero. Based on the MCB intervals formed, the mean retrieval time for a 12 by 12, 5-deep storage system, for example, performs as much as 105 seconds better using a move-to-front retrieval rule than it does using a naïve retrieval rule. The move-to-front rule provides significant reduction in mean retrieval time over the naïve retrieval time for storage systems with accessibility constants greater than one.

Table 6 displays the average improvement in mean retrieval between each of the 2,825 systems compared in scenarios Naïve-Pareto and MTF-Pareto. The move-to-front retrieval rule provides significant improvement in mean retrieval time under Pareto demand conditions especially for increasing levels of k.

Accessibility Constant (k)	Average Improvement in Mean Retrieval Time (measured in seconds)	Average Improvement in Retrieval Time as a % of the total
1	0.00	0.00%
2	17.35	5.29%
3	40.57	10.67%
4	69.77	15.92%
5	105.33	20.87%

Table 6 Average Improvement in Retrieval Time of the MTF Retrieval Rule vs. the Naïve Retrieval Rule in Pareto Demand Conditions

4. Additional Findings: Scenario MTF-Pareto

Since the move-to-front retrieval rule provided significant benefit for increasing levels of *k*, we analyzed the MTF-Pareto observations in greater detail. The objective was to determine which storage systems provided the best mean retrieval times. Figure 19 is a plot of all 2,825 observations taken from the MTF-Pareto scenario and Figure 20 is a similar plot but provides a closer view of the storage systems with the best mean retrieval times.

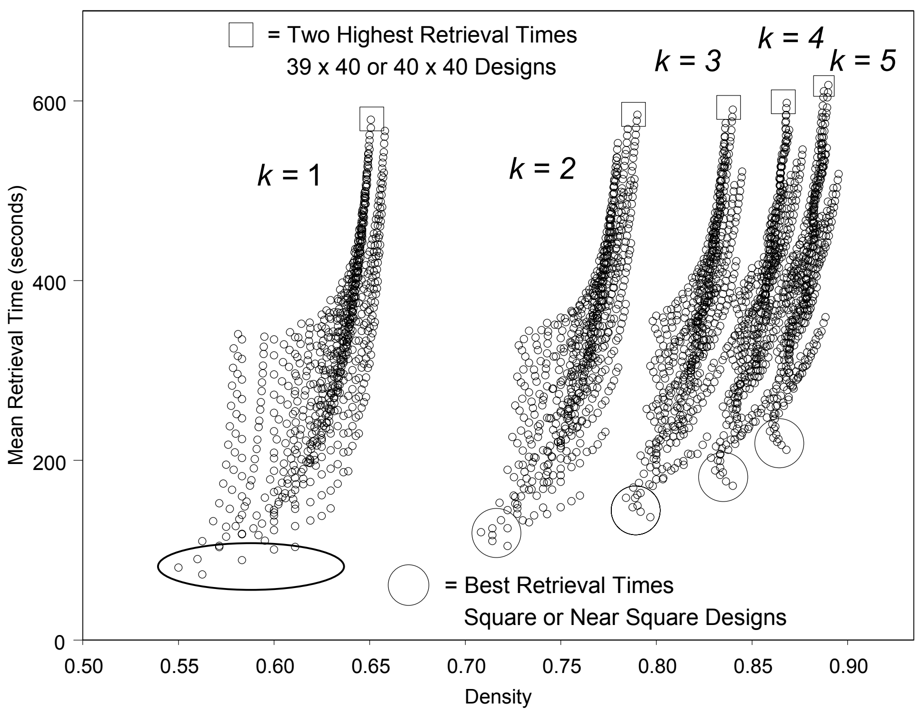

Figure 19 Mean Retrieval Times of All 2,825 Storage Systems Examined for the MTF-Pareto Scenario

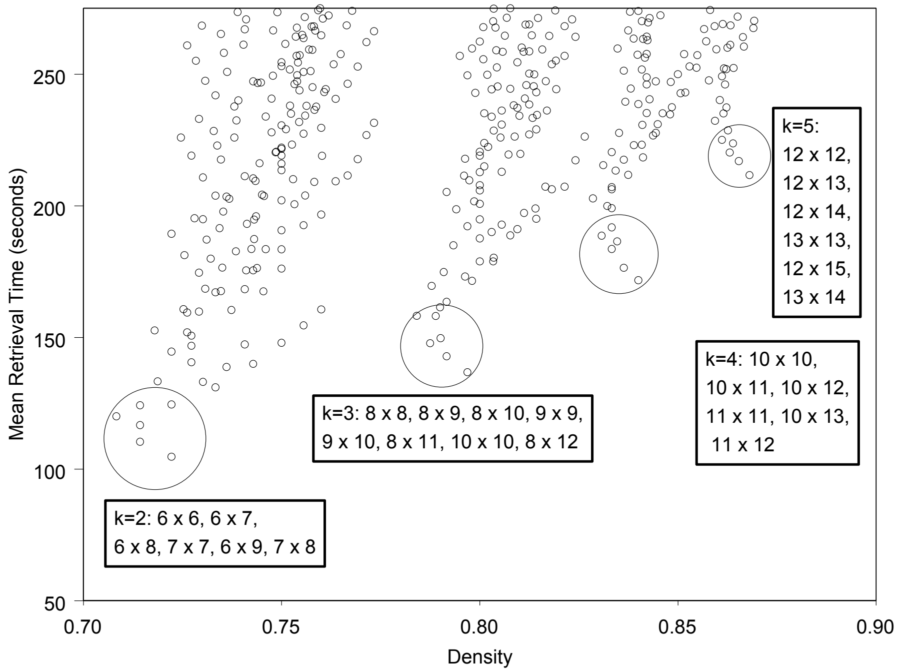

Figure 20 Best Mean Retrieval Times of the MTF-Pareto Scenario

Figures 19 and 20 are very similar to the plots displayed earlier in this Chapter for the observations associated with the Naïve-Uniform scenario. However, we note that the mean retrieval times of the storage systems with storage densities greater than 70% (i.e. those storage system with $k > 1$) are significantly lower (compare Figure 17 and Figure 19). A set of storage systems, for an accessibility constant greater than one, that standout with the lowest mean retrieval times are those systems circled and labeled in Figure 20 above. These storage systems are the smallest square or near square *m* x *n* designs produced by the packing algorithm for each accessibility constant. The storage systems with the highest mean retrieval times were the largest *m* x *n, k*-deep systems examined in this thesis; the 39 by 40 and 40 by 40 storage systems.

Illustrations of the best storage designs (i.e. lowest retrieval time) for each accessibility constant are displayed below. The storage systems with the lowest mean retrieval time in any of the four scenarios examined had the same pallet configuration. This design has the shape, roughly, of an inverted "T". These were also the smallest systems the packing algorithm produced for each the five accessibility constants examined (i.e. there is not a 10 by 10, 5-deep system since a 12 by 12 storage system is the smallest *m* x *n* design that supports an accessibility constant of five).

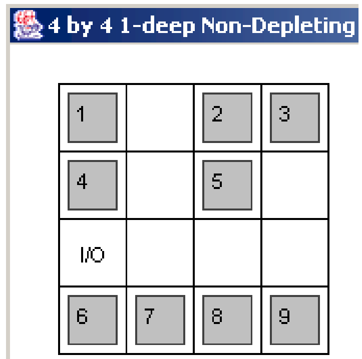

Figure 21 Storage Configuration with the Lowest Retrieval Time for k = 1

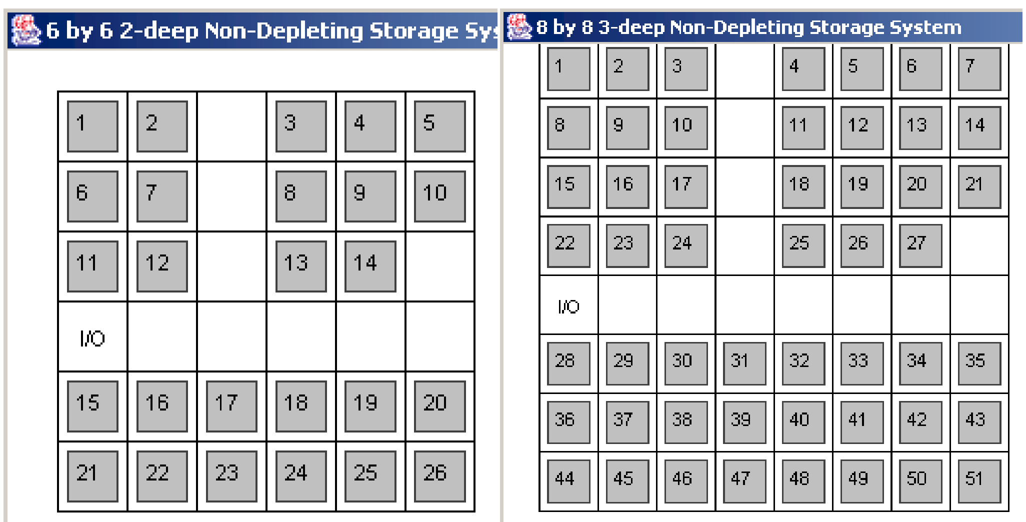

Figure 22 Storage Configurations with the Lowest Retrieval Time for k = 2 and 3

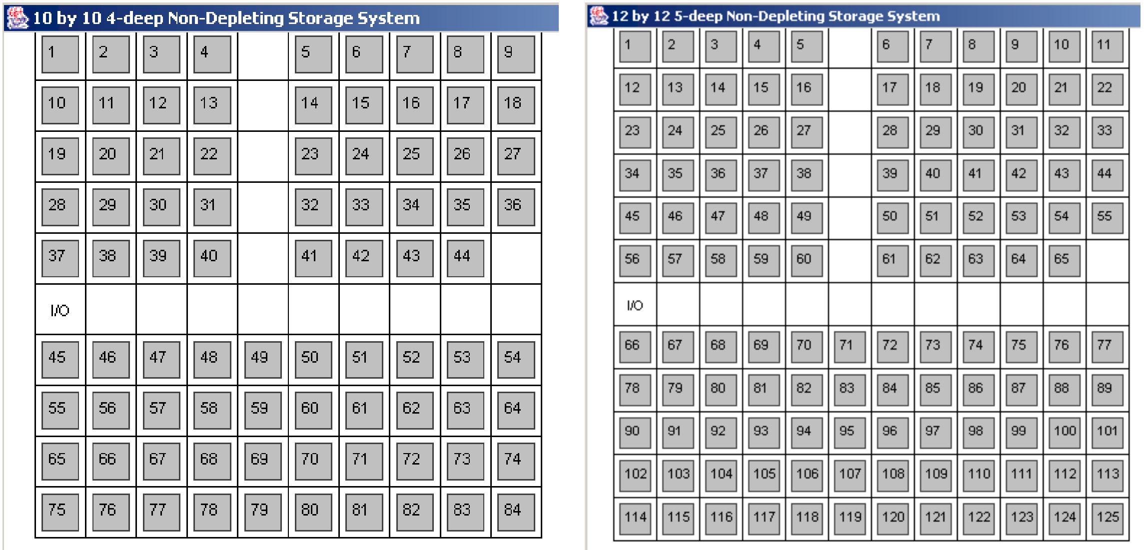

Figure 23 Storage Configurations with the Lowest Retrieval Time for k = 4 and 5

m x n ***k = 1***	***m x n*** ***k = 2***	***m x n*** ***k = 3***	***m x n*** ***k = 4***	***m x n*** ***k = 5***
4 x 4	6 x 6	8 x 8	10 x 10	12 x 12
4 x 5	6 x 7	8 x 9	10 x 11	12 x 13
4 x 6	6 x 8	8 x 10	10 x 12	12 x 14
5 x 5	7 x 7	9 x 9	11 x 11	13 x 13
5 x 6	6 x 9	9 x 10	10 x 13	12 x 15
4 x 7	7 x 8	8 x 11	11 x 12	13 x 14
6 x 6	6 x 10	10 x 10	12 x 12	12 x 16
5 x 7	7 x 9	8 x 12	11 x 13	13 x 15
4 x 8	8 x 8	9 x 11	10 x 14	14 x 14
6 x 7	6 x 11	8 x 13	12 x 13	13 x 16

Table 7 Best Ten Storage Designs per k, Scenario 2B

All storage systems were examined by accessibility constant and rank ordered to form five subsets of the 10 storage systems with the lowest retrieval times. The five subsets are displayed in Table 7. The objective was to analyze each group in more detail and select the outright best system for each accessibility level. The assumption we made was that the best system would be contained in one of the ten systems with the lowest mean retrieval times. Each subset was analyzed utilizing the NM + MCB procedure to select the best performing systems based on the lowest mean retrieval times. Simultaneous confidence intervals were formed with an indifference parameter of 15 seconds and a probability of correct selection of 97.5%. A value of 3.07 for g_α was utilized based on $n_o = 50$, $k = 10$, and $\alpha = .025$. No additional observations were required. The complete results along with illustrations of each of the pallet configurations are provided below.

a. *Summary of Best Storage Systems*

There was no single best storage system for any of the comparisons for each accessibility constant examined. Instead, the NM + MCB procedure produced subsets that contained between three and five storage systems. The subsets are displayed in Table 8. Each subset contains the smallest square or near square designs with an inverted "T" shape pallet configuration.

m x n ***k = 1***	***m x n*** ***k = 2***	***m x n*** ***k = 3***	***m x n*** ***k = 4***	***m x n*** ***k = 5***
4 x 4	6 x 6	8 x 8	10 x 10	12 x 12
4 x 5	6 x 7	8 x 9	10 x 11	12 x 13
4 x 6	7 x 7	8 x 10	10 x 12	12 x 14
5 x 5		9 x 9		12 x 15
				13 x 13

Table 8 Summary of the Best Storage Systems for each Accessibility Constant.

b. *NM + MCB Results, k = 1 designs*

m x n ***k = 1***	**Pallets**	**Pallets²** **(*m x n*)**	**Density**	**Retrieval Time**	**Lower MCB**	**Diff**	**Upper MCB**
4 x 4	9	16	0.564	74.66	-20.55	-5.55	9.45
4 x 5	11	20	0.550	80.21	-9.45	5.55	20.55
4 x 6	14	24	0.583	88.36	-1.30	13.70	28.70
5 x 5	14	25	0.560	89.33	-0.33	14.67	29.67
5 x 6	18	30	0.600	99.40	0	24.74	39.74
4 x 7	16	28	0.571	103.05	0	28.39	43.39
6 x 6	20	35	0.611	103.79	0	29.13	44.13
5 x 7	22	36	0.571	104.52	0	29.86	44.86
4 x 8	18	32	0.563	109.41	0	34.75	49.75
6 x 7	25	42	0.595	111.00	0	36.34	51.34

Table 9 Retrieval Times and NM + MCB Results, Best k = 1 Designs

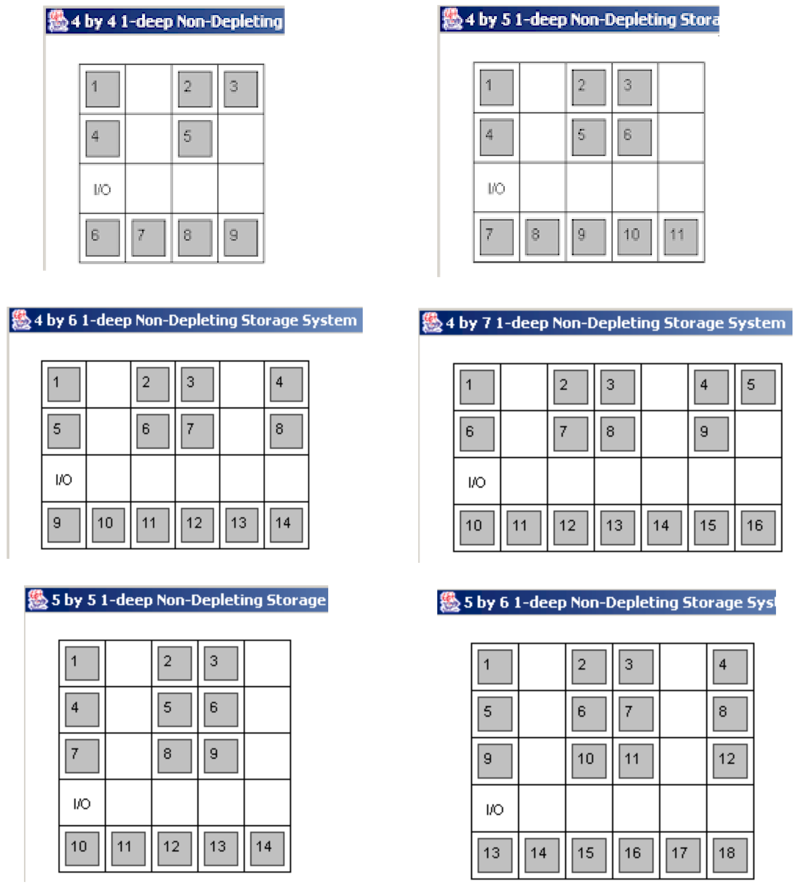

Figure 24 The Ten Best $k = 1$ Storage Designs, Part 1

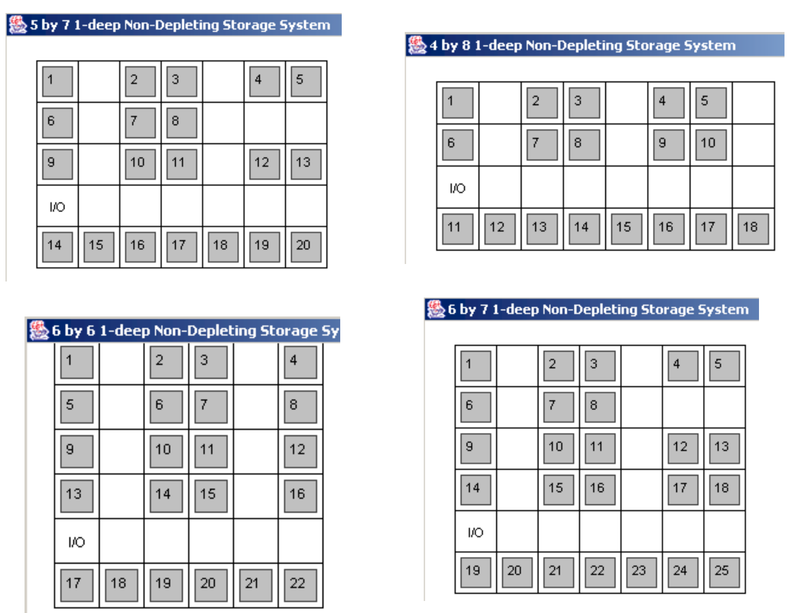

Figure 25 The Ten Best $k = 1$ Storage Designs, Part 2

The results of the NM + MCB procedure, for the ten single access systems analyzed, are displayed in Table 9. Four MCB confidence intervals contain zero indicating there is no single best system. Instead the best system is contained in a subset comprised of the 4 by 4, 4 by 5, 4 by 6 and 5 by 5 single access storage systems. These four storage systems are all better than the remaining storage systems we compared them against whose lower MCB bounds are zero. If we are indifferent between the four storage systems (i.e. the difference between two systems is less than 15 seconds), we select the storage system that holds the greatest number of pallets. The 4 by 6 single access storage system holds the most pallets and has the highest density within the subset. By choosing the 4 by 6 storage system from the subset rather than the system with the lowest mean retrieval time, our sustainment increases by 56% while the mean retrieval time increases by only 21%.

c. *NM + MCB Results, k = 2 designs*

m x n ***k = 2***	**Pallets**	**Pallets^2 (*m x n*)**	**Density**	**Retrieval Time**	**Lower MCB**	**Diff**	**Upper MCB**
6 x 6	26	36	0.722	105.70	-20.84	-5.84	9.16
6 x 7	30	42	0.714	111.53	-9.16	5.84	20.84
7 x 7	35	49	0.714	116.74	-3.96	11.04	26.04
6 x 8	34	48	0.708	120.77	0	15.08	30.08
7 x 8	40	56	0.714	124.41	0	18.71	33.71
6 x 9	39	54	0.722	125.96	0	20.27	35.27
7 x 9	46	63	0.730	131.62	0	25.92	40.92
8 x 8	46	64	0.719	132.09	0	26.40	41.40
6 x 10	44	60	0.733	133.14	0	27.45	42.45
8 x 9	53	72	0.736	138.51	0	32.81	47.81

Table 10 Overall Sample Retrieval Times and MCB Results, Best k = 2 Designs

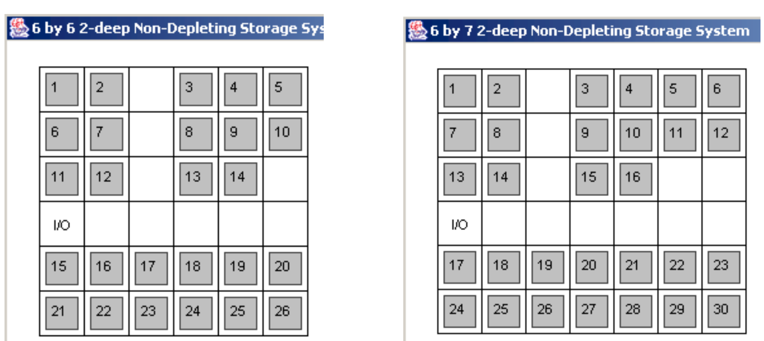

Figure 26 The Ten Best k = 2 Storage Designs, Part 1

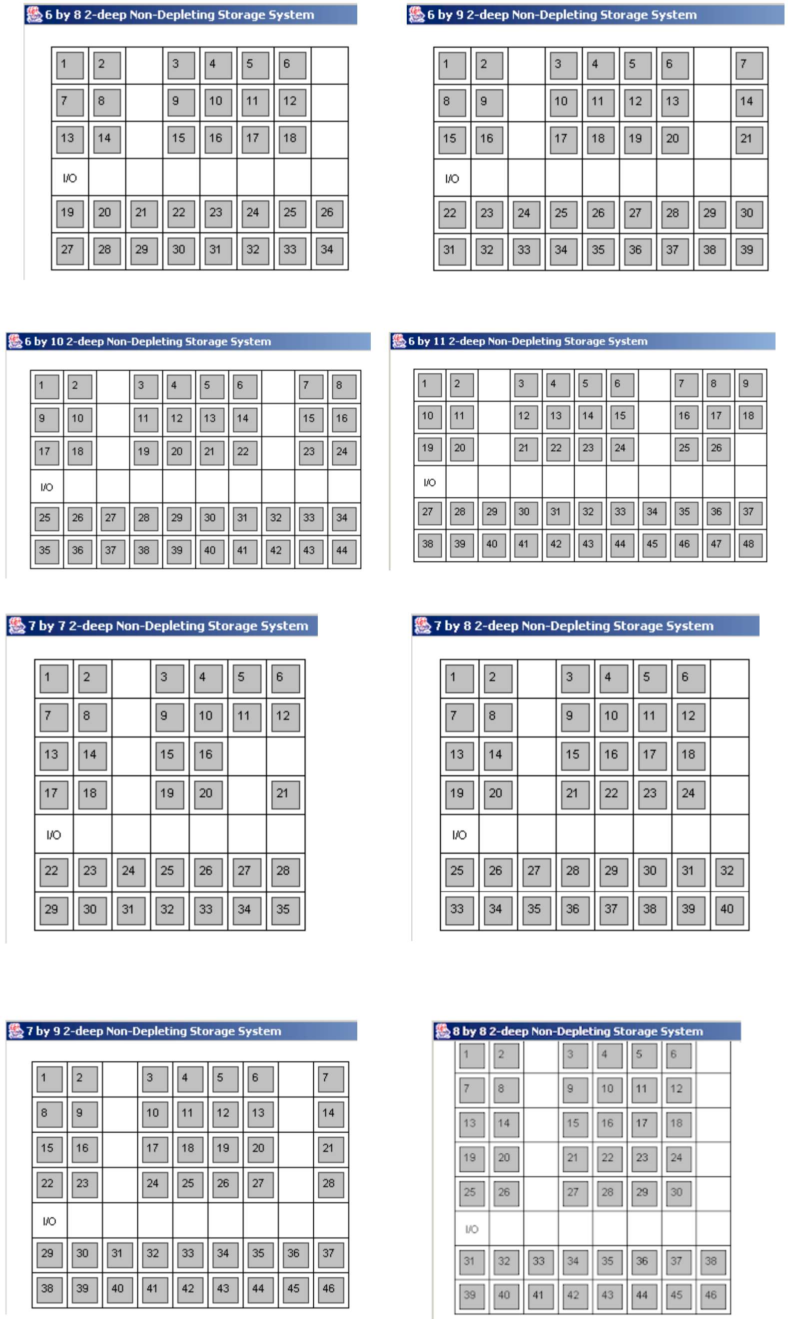

Figure 27 The Ten Best $k = 2$ Storage Designs, Part 2

The mean retrieval time and MCB results for the ten $k = 2$ storage systems are displayed in Table 10. The best system is contained in a subset comprised of the 6 by 6, 6 by 7, and 7 by 7, 2-deep storage systems.

d. *NM + MCB Results, k = 3 Designs*

m x n *k = 3*	Pallets	Pallets[2] (*m x n*)	Density	Retrieval Time	Lower MCB	Diff 1B-2B	Upper MCB
8 x 8	51	64	0.797	136.09	-19.19	-4.19	10.81
8 x 9	57	72	0.792	140.28	-10.81	4.19	19.19
8 x 10	63	80	0.788	145.81	-5.28	9.72	24.72
9 x 9	64	81	0.790	147.99	-3.11	11.89	26.89
9 x 10	71	90	0.788	156.11	0	20.02	35.02
8 x 11	69	88	0.784	156.66	0	20.56	35.56
10 x 10	79	100	0.790	160.66	0	24.57	39.57
8 x 12	76	96	0.792	161.21	0	25.12	40.12
9 x 11	78	99	0.788	168.07	0	31.98	46.98
8 x 13	83	104	0.798	169.85	0	33.76	48.76

Table 11 Overall Sample Retrieval Times and MCB Results, Best $k = 3$ Designs

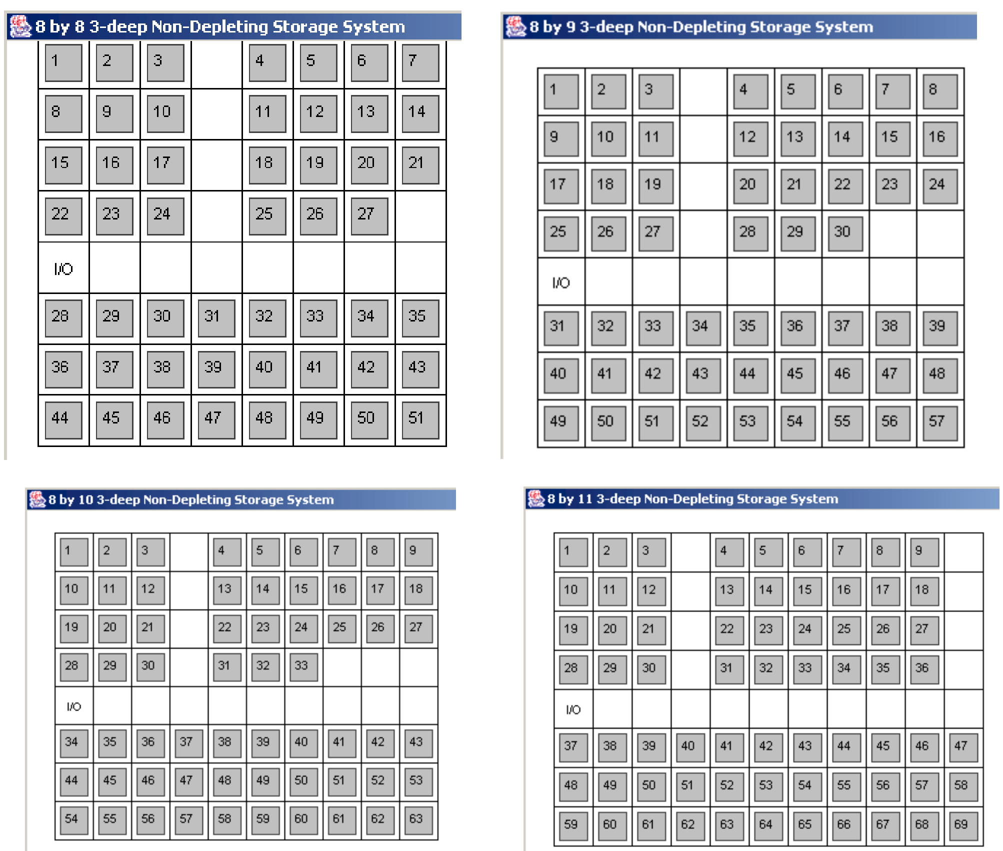

Figure 28 The Ten Best $k = 3$ Storage Designs, Part 1

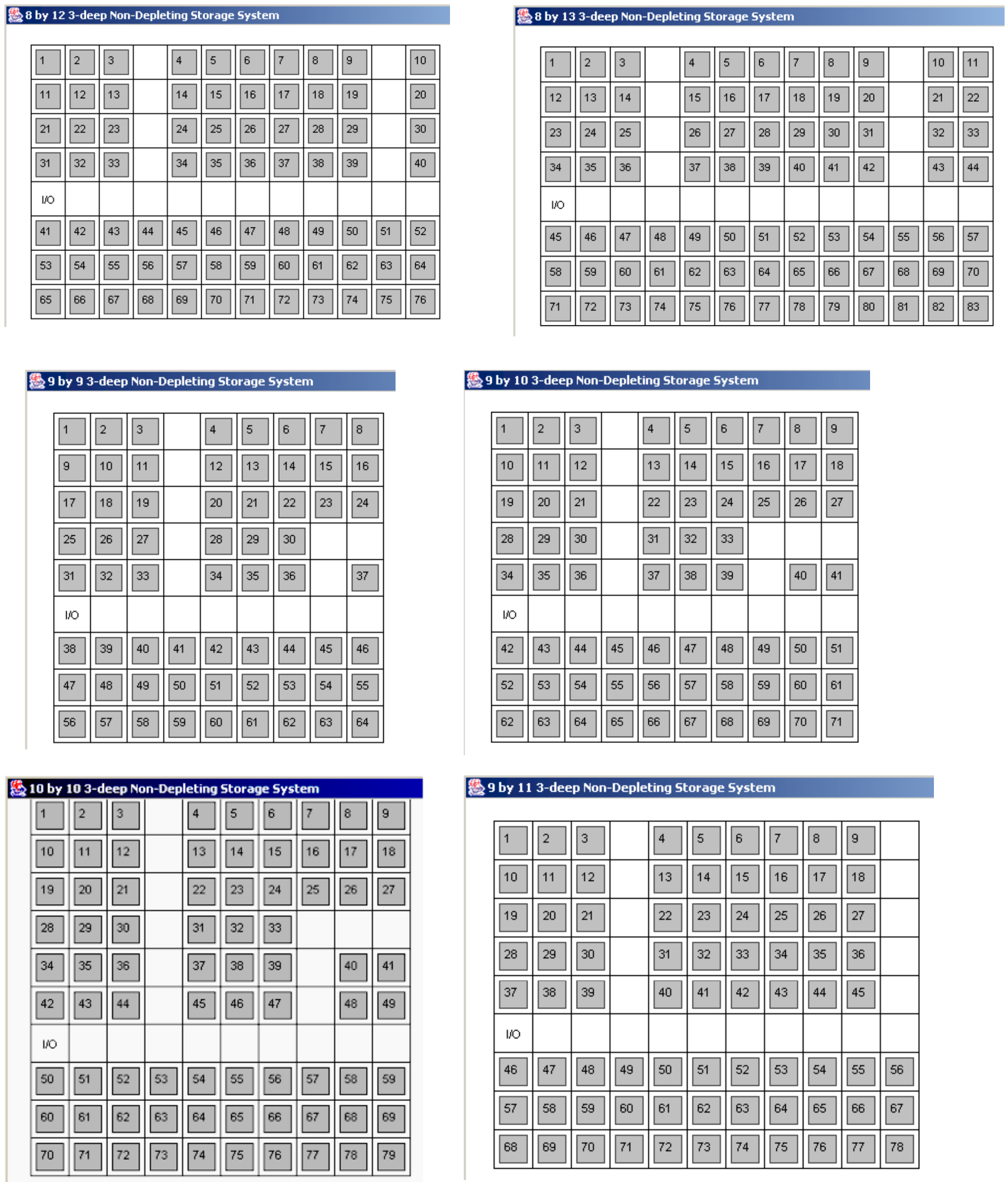

Figure 29 The Ten Best $k = 3$ Storage Designs, Part 2

The results are displayed in Table 11. Four MCB confidence intervals contain zero indicating there is no single best system and the best system is contained in a subset comprised of the 8 by 8, 8 by 9, 8 by 10 and 9 by 9, 3-deep storage systems.

e. *NM + MCB Results, k = 4 Designs*

m x n ***k = 4***	**Pallets**	**Pallets[2] (*m x n*)**	**Density**	**Retrieval Time**	**Lower MCB**	**Diff 1B-2B**	**Upper MCB**
10 x 10	84	100	0.840	169.85	-20.08	-5.08	9.92
10 x 11	92	110	0.836	174.93	-9.92	5.08	20.08
10 x 12	100	120	0.833	180.41	-4.44	10.56	25.56
11 x 11	101	121	0.835	185.49	0	15.64	30.64
10 x 13	108	130	0.831	186.46	0	16.61	31.61
11 x 12	110	132	0.833	190.96	0	21.11	36.11
12 x 12	120	144	0.833	197.48	0	27.63	42.63
11 x 13	119	143	0.832	199.13	0	29.28	44.28
10 x 14	116	140	0.829	201.47	0	31.62	46.62
12 x 13	130	156	0.833	204.78	0	34.93	49.93

Table 12 Retrieval Times and NM + MCB Results, Best *k* = 4 Designs

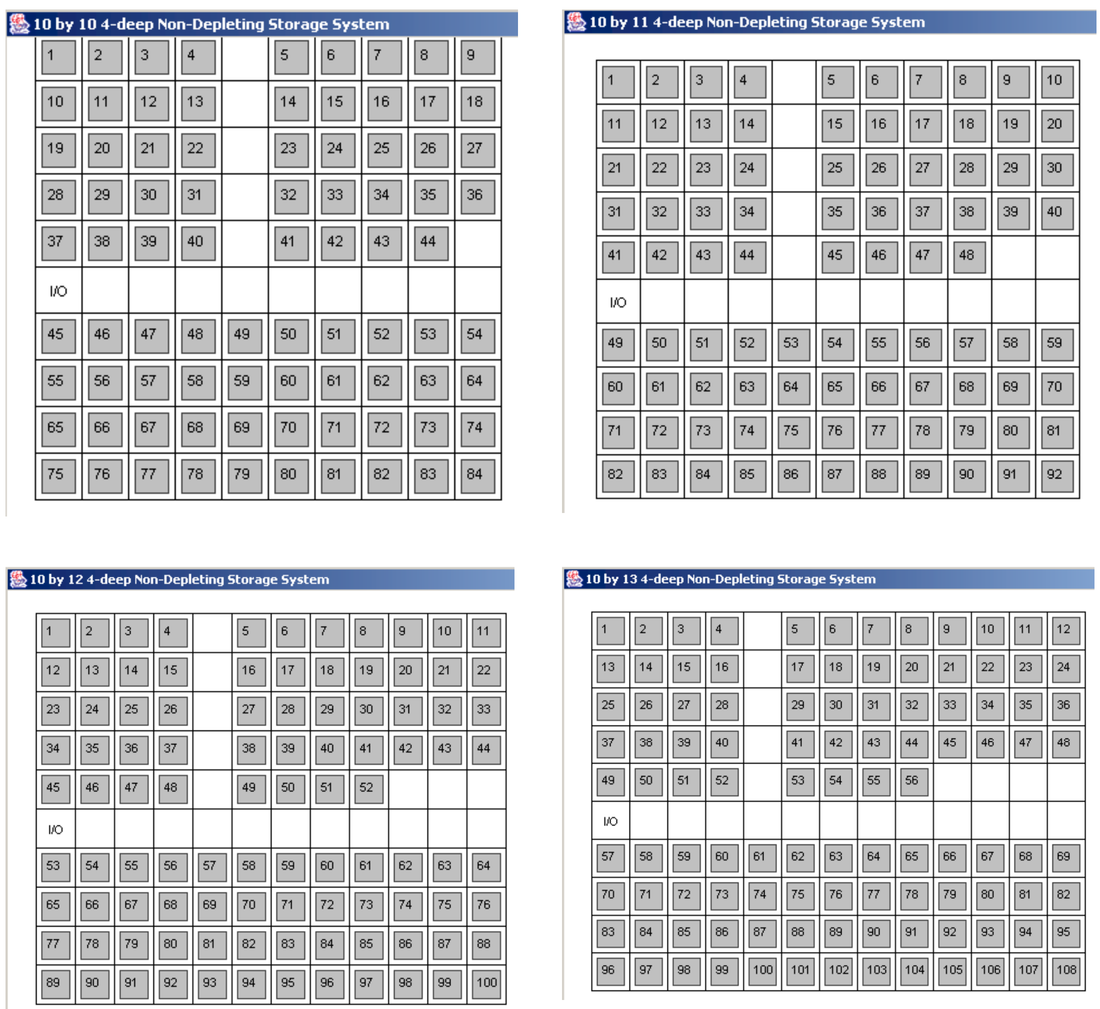

Figure 30 The Ten Best *k* = 4 Storage Designs, Part 1

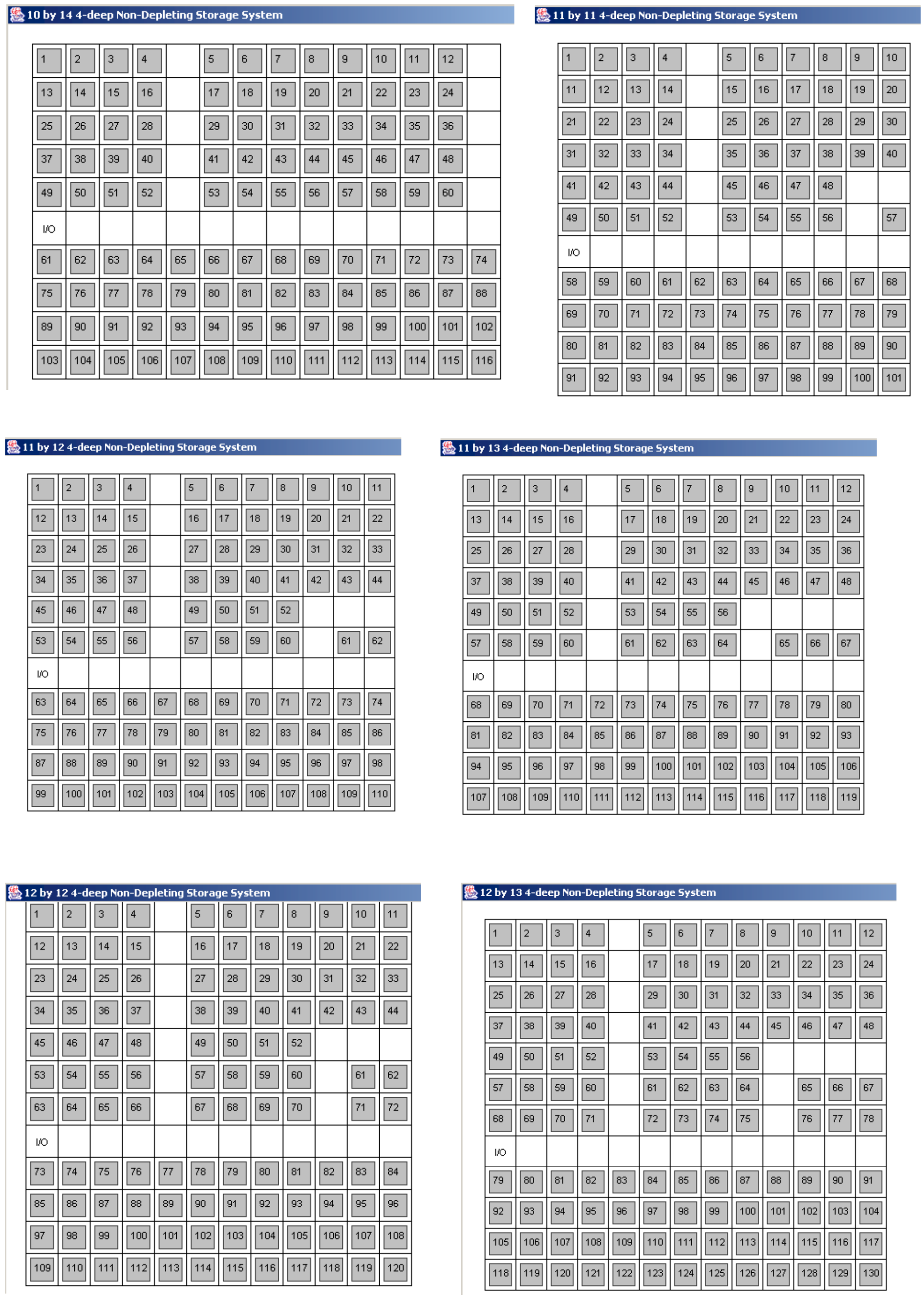

Figure 31 The Ten Best $k = 4$ Storage Designs, Part 2

The best systems are the 10 by 10, 10 by 11, and 10 by 12, 4-deep storage systems which all have an inverted “T” shape design.

f. NM + MCB Results, k = 5 Designs

m x n *k = 5*	Pallets	Pallets^2 (*m x n*)	Density	Retrieval Time	Lower MCB	Diff 1B-2B	Upper MCB
12 x 12	125	144	0.868	210.14	-19.48	-4.48	10.52
12 x 13	135	156	0.865	214.62	-10.52	4.48	19.48
12 x 14	145	168	0.863	218.13	-7.01	7.99	22.99
12 x 15	155	180	0.861	222.76	-2.37	12.63	27.63
13 x 13	146	169	0.864	223.26	-1.88	13.12	28.12
13 x 14	157	182	0.863	228.74	0	18.61	33.61
12 x 16	165	192	0.859	229.36	0	19.23	34.23
13 x 15	168	195	0.862	236.27	0	26.13	41.13
14 x 14	169	196	0.862	237.01	0	26.87	41.87
13 x 16	179	208	0.861	240.88	0	30.74	45.74

Table 13 Overall Sample Retrieval Times and MCB Results, Best $k = 5$ Designs

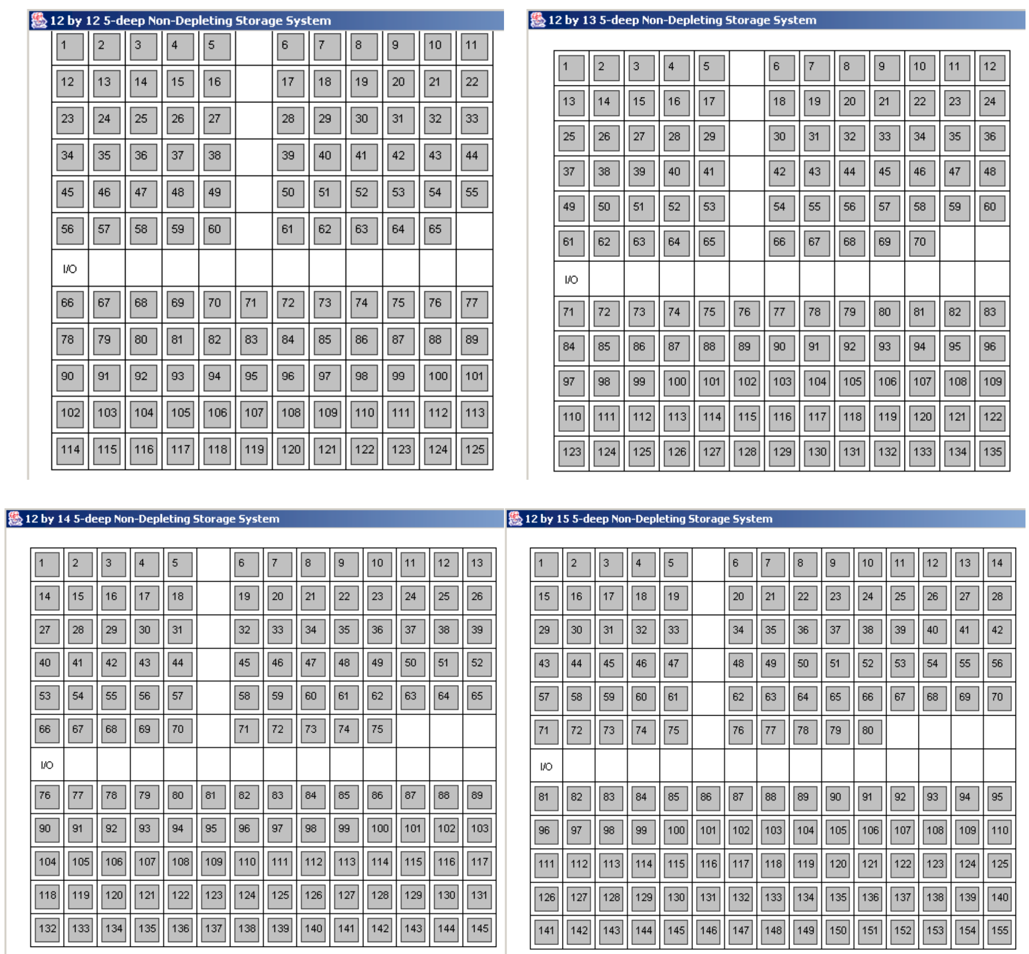

Figure 32 The Ten Best $k = 5$ Storage Designs, Part 1

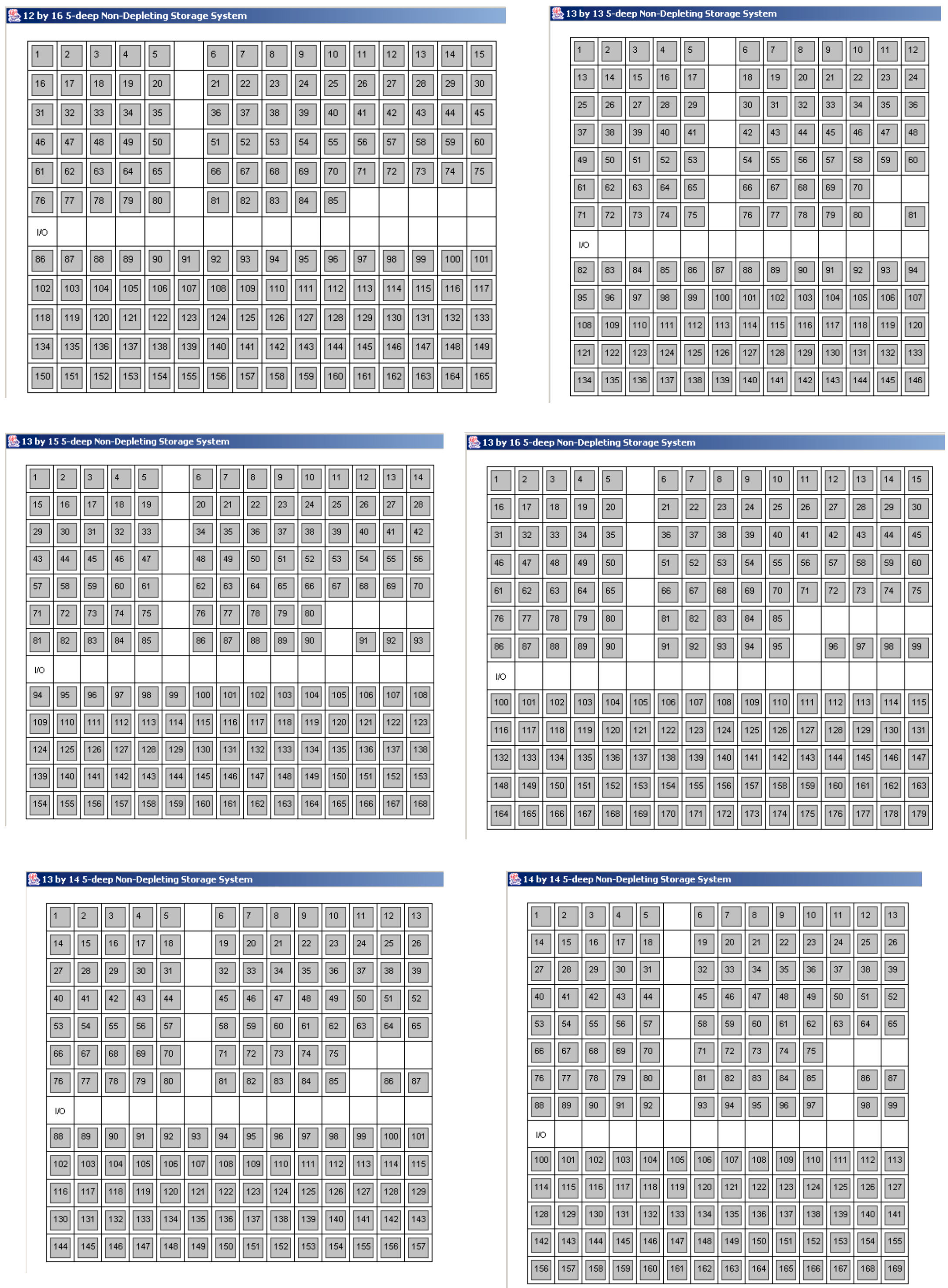

Figure 33 The Ten Best $k = 5$ Storage Designs, Part 2

Five MCB confidence intervals contain zero indicating there is no single best system and the best system is contained in a subset comprised of the 12 by 12, 12 by 13, 12 by 14, 12 by 15, and 13 by 13, 5-deep storage systems. Again, the inverted "T" design is prominent.

5. An Additional Comparison

The smallest square designs satisfying the constraints of the packing algorithm performed the best across all scenarios and levels of accessibility. How would the best square designs (8 by 8, 10 by 10, etc.) perform when compared against a storage system with the same m x n dimensions but greater levels of accessibility (i.e. compare a 10 by 10, 4-deep to a 10 by 10, 3-deep, to a 10 by 10,2-deep, and to a 10 by 10, 1-deep)? The objective is to determine if the move-to-front retrieval rule under Pareto demand conditions could produce mean retrieval times that were close enough to the lower density storage systems that we would be indifferent between choosing either of the two systems.

To examine this question, we chose a 12 by 12 design since it supports all five levels of accessibility. Simultaneous MCB confidence intervals were formed with an indifference parameter of 15 seconds and a probability of correct selection of 97.5% ($\alpha = .025$). A value of 2.81 for g_α was utilized based on $n_o = 50$, $k = 5$, and $\alpha = .025$. The results are summarized in Table 14 and Table 15.

12 x 12 (Scenario MTF-Pareto)	**k=1**	**k=2**	**k=3**	**k=4**	**k=5**
Mean Retrieval Time	186.67	186.34	192.34	197.48	210.14
# Pallets	92	107	116	120	125
Density	63.9%	74.3%	80.6%	83.3%	86.8%

Table 14 The Percentage Change in Mean Retrieval Time and Density of All 12 by 12 Storage Systems with Increasing k

m	*n*	*k*	**Pallets**	**Pallets^2 (*m x n*)**	**Retrieval Time**	**Lower MCB**	**Diff**	**Upper MCB**
12	12	1	92	144	186.67	-14.66	0.34	15.34
12	12	2	107	144	186.34	-15.34	-0.34	14.66
12	12	3	116	144	192.34	-9.00	6.00	21.00
12	12	4	120	144	197.48	-3.86	11.14	26.14
12	12	5	125	144	210.14	0.00	23.80	38.80

Table 15 NM + MCB Results of a Comparison of All 12 by 12 Storage Systems

Based on the MCB results, there is not a single best storage system but a subset of four designs that include accessibility levels from one to four. We can say that the best storage system is contained in this subset. The densities of the storage systems range from 64% to 83%. The difference between the mean retrieval time of the 12 x 12, 4-deep storage system and the 12 x 12, single access storage systems is less than 11 seconds. In other words, the mean retrieval time of the higher density system is only 6% higher than the mean retrieval time of the lower density system but the higher density storage system contains 28 more pallets, an increase of 30%.

Figure 34 displays the percentage change in both retrieval time and total pallets as *k* is increased from one to five. Based on Figure 34, we achieve significant gains in density with only small penalty increases in retrieval times as the accessibility constant (*k*) is increased from one to two to three. However, the percentage change in density begins to flatten when *k* is four while the percentage change in retrieval times begins to increase. When *k* is increased to five, we see even greater increases in retrieval time with little additional gain in density.

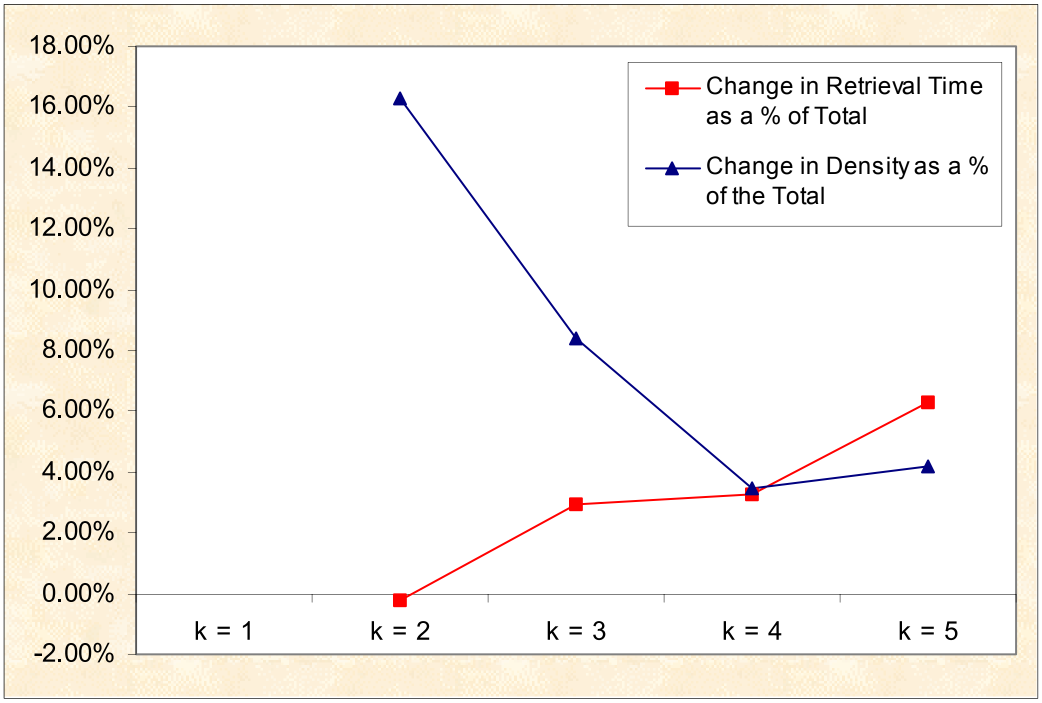

Figure 34 Percentage Change in Retrieval Time vs. the Percentage Change in Density Comparison as *k* is Increased From One to Five for a 12 by 12 Storage System in the MTF-Pareto Scenario

We compared the percentage change in mean retrieval time and density for all 8 by 8, 10 by 10, and 14 by 14 systems for all *k* such that $k < (m-1)/2$. The results are displayed in Table 16, Table 17, and Table 18. In each instance, there are significant increases in density as *k* is increased from one to two and only small increases in mean retrieval time. Of the four cases analyzed, the maximum increase in mean retrieval time, as *k* is increased from one to two, was no more than four seconds while the minimum increase in density was at least 12% and at least eight pallets.

8 x 8 (Scenario MTF-Pareto)	**k=1**	**k=2**	**k=3**
Mean Retrieval Time	130.7	133.33	136.74
# Pallets	38	46	51
Density	59.4%	71.9%	79.7%

Table 16 The Percentage in Mean Retrieval Time and Density of All 8 by 8 Storage Systems with Increasing *k*

10 x 10 (Scenario MTF-Pareto)	k=1	k=2	k=3	k=4
Mean Retrieval Time	156.63	160.62	161.42	171.66
# Pallets	61	76	79	84
Density	61.0%	76.0%	79.0%	84.0%

Table 17 The Percentage in Mean Retrieval Time and Density of All 10 by 10 Storage Systems with Increasing *k*

14 x 14 (Scenario MTF-Pareto)	k=1	k=2	k=3	k=4	k=5	k=6
Mean Retrieval Time	216.61	218.92	226.27	239.51	237.36	255.28
# Pallets	122	149	162	164	169	174
Density	62.2%	76.0%	82.7%	83.7%	86.2%	88.8%

Table 18 The Percentage in Mean Retrieval Time and Density of All 14 by 14 Storage Systems with Increasing *k*

By examining the changes, as *k* is increased, we find the overall benefit in density is less and less while the mean retrieval time begins to significantly increase. The difficult question is to determine at what value of *k* the increase or cost in terms of a higher in mean retrieval time exceeds the gain in density (i.e. more pallets). Based on these four cases examined and the analysis conducted earlier in this Chapter, we believe that value for *k* to be two, three, or four depending on the storage system. These levels provide for storeroom densities in the 70% to 85% range. Higher levels of *k* produce densities above 85%. These higher density storerooms become so dense the storage system must make a large number of moves internally to reposition its contents to get any one pallet. While less dense storage systems, those with densities less than 70%, reduce MPF(F)'s ability to carry out its primary mission to preposition material and sustain forces.

If the goal is to produce acceptable retrieval times and some minimum level of sustainment, storage configurations with storage densities between 70% and 85% (i.e. k = 2, 3, or 4) will in all likelihood satisfy both competing goals. Densities above 85% may only make sense for depleting systems or for low demand and low priority items.

B. A FINAL OBSERVATION

A final observation relates to the distribution of the process times for each storage system. The distribution of process times is based on the size of the storage system (m x n) and the level of accessibility to any given pallet in the storeroom (k). For the storage system with the greatest level of accessibility ($k = 1$), the process time of any pallet in the storeroom is simply the time it takes for an AS/RS system to pick the item, retrieve it and restow it. For systems with lower levels of accessibility ($k > 1$), the process times also include the time it takes for the AS/RS system to reposition any pallets that block access to the requested pallet. The distribution of process times is also based on our choice of using a single I/O point design.

Those pallets located closest the I/O point have the shortest distance to travel when selected for retrieval while those located farthest from the I/O point have much greater distances to travel to the I/O point and therefore higher retrieval times. The fact that our initial analysis and the NM + MCP procedure identified the smallest m x n designs for each level of accessibility as the best performers is not surprising. The smallest designs that meet the packing algorithm constraints where $m > 2k+1$ and $n \geq m$ minimize not only the overall size of the storeroom but also the mean retrieval time for that system. The smallest designs ensure no one pallet is located too far from the I/O point.

Figure 35 illustrates the distribution of process times for four 3-deep storage systems. The darker shading indicates pallets with higher process times. A pallet that occupies a location adjacent an aisle does not necessarily have lighter shading. Storage systems with single I/O points penalize locations farthest from the I/O point. The locations with the highest process times are typically found in the top left corner, the top right corner, or the top center. The bottom right corner of a long rectangular storage system (n much greater than m) also had higher process times. For square or near square designs, the process times of the pallets stored along of the bottom of an m x n storage system had lower process times than those pallets located along the top of the storage system.

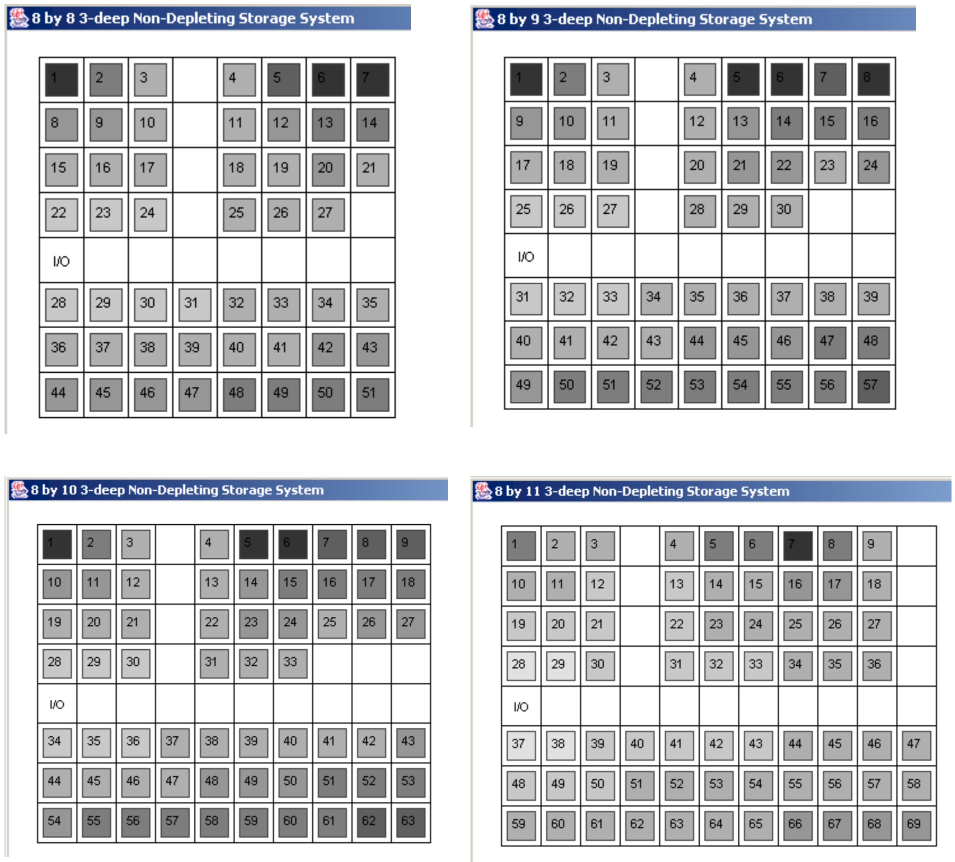

Figure 35 Display of the Distribution of Retrieval Times

IV. CONCLUSIONS

We analyze the trade-off between storage density (i.e. how much we can store) and mean retrieval time (i.e. how fast we can retrieve it) in notional storerooms aboard a future sea base. Future sea base platforms, like MPF(F), require substantial sustainment capabilities to support the concepts of Expeditionary Maneuver Warfare and Sea Basing. The future sea base must also have a selective offload capability to quickly and efficiently respond to the needs of forces ashore. These are competing objectives for which future sea base platforms must be designed to achieve a balance.

Based on analysis of the models, we recommend a range of storage densities for use as general planning parameters to guide future decisions relating to the size of the storage areas required on future sea base platforms. These storage densities offer a balance between response time and overall sustainment capacity. In addition, we provide insight into the types of storeroom configurations that provide the best mean retrieval times and how a simple retrieval rule can significantly reduce mean retrieval times under Pareto-like demand conditions. Our results also show that square or near square storage systems with inverted "T" shape storeroom designs, as illustrated in Figure 36, produce better mean retrieval times for a given accessibility constant (k).

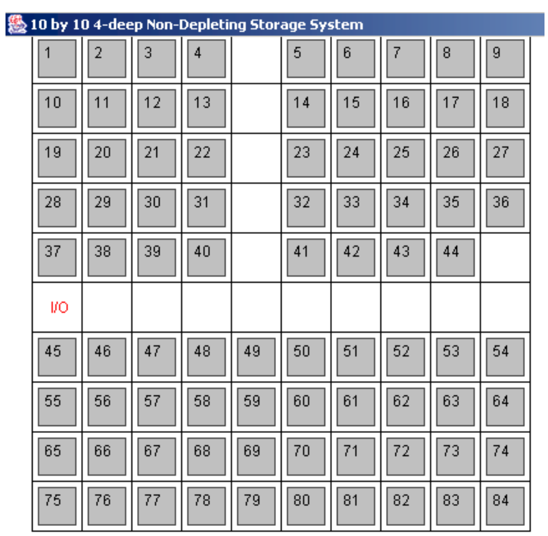

Figure 36 Illustration of a Storage System with an Inverted "T" Design

Conclusion 1: *Designs with storage densities between 70% and 85% best support the requirements for selective offload.*

The storage systems examined in this thesis had storage densities that ranged from 56% to 89%, which is a direct output of the packing algorithm used to generate the storage configurations. The density of a storage system is directly related to the accessibility constant, *k,* and for this thesis, we explored five different levels of *k*. As the storage density of a system increases, the response time to retrieve any pallet also increases. Smaller values of *k* are associated with lower retrieval times while higher values of *k* are associated with higher retrieval times.

By examining the changes in storage density and retrieval time as *k* is increased, we find the overall benefit in density less and less (i.e. storage density increasing at a decreasing rate) while the mean retrieval time begins to significantly increase (i.e. increasing at an increasing rate). This is an important observation directly related to the fundamental design issue that lies at the heart of the storage density versus response time tradeoff.

Single access storage systems, those with $k = 1$, have storage densities less than 70%. Although one might consider these very accessible storage configurations for the most time sensitive items, we recommend using a more dense storage system design ($k = 2$) instead. The difference in mean retrieval time between these two storage systems is relatively small while the difference in the amount of material stored is quite large. Single access storage systems penalize MPF(F)'s overall sustainment capability with little gain in mean response time.

Storage systems with storage densities in the 80% to 85% range, those systems with $k = 3$ or $k = 4$, provide the best "bang for the buck". When retrieval time is not as important, these storage systems offer much greater sustainment capacities without significantly higher response time. Storage systems with densities greater than 85%, on the other hand, have increasingly higher mean retrieval times with little additional gain in total material stored. These dense storage systems must make a large number of moves internally to reposition its contents to get any one pallet.

Storage systems with storage densities between 70% and 80% (i.e. $k = 2$) should be utilized for high priority or time sensitive items while storage systems with densities between 80% and 85% (i.e. $k = 3$ or $k = 4$) should be used for items where retrieval time is not as important but a selective offload capability is still required. The highest density storage systems, those with storage densities greater than 85%, should be reserved for items that require no selective offload capability.

Our results suggest that the best value for k then is two, three or four, which generally provide for storeroom densities in the 70% to 85% range. It is in this range where a balance between storage density and response time is achieved. Since planning factors do not currently exist to guide decisions relating to the size of the storage areas required on future sea base platforms, we recommend these storage densities as general planning parameters.

Conclusion 2: *The best performing storage systems are small square or near square designs.*

The small square or near square storage systems had the lowest mean retrieval times for each of the accessibility constants examined. By small, we mean the smallest storage systems the packing algorithm supported for each accessibility constant (i.e. there is not a 10 by 10, 5-deep system since a 12 by 12 storage system is the smallest m x n design that supports an accessibility constant of five). This result is directly related to conclusion five. The larger rectangular storage systems penalize items stored farther from the I/O point and result in higher mean retrieval times.

Conclusion 3: *The best performing storage systems have the same general pallet configuration.*

The square or near square storage systems not only produced the best mean retrieval times but also had the same pallet configuration in the shape of an inverted "T" like the storage system displayed in Figure 36. The packing algorithm produces these configurations when the width (the variable m) is twice the accessibility constant plus one (i.e. $m = 2(k+1)$) and the difference between the length (the variable n) and the width is strictly less than k (i.e. $n - m < k$). The inverted “T” shape is produced when only these conditions are met.

Conclusion 4: *Under Pareto-like demand conditions, the move-to-front retrieval rule provides significant reductions in mean retrieval time for storage systems with $k \geq 2$.*

The total savings in retrieval time was greater for higher density storage systems (i.e. as k is increased the average improvement in mean retrieval time as a percentage of the total increases). For example, there was, on average, a 5.3% reduction in mean retrieval time for storage systems with $k = 2$ and a 20.9% reduction in mean retrieval time for storage systems when $k = 5$. The average improvement between each level of k is approximately 5%. The move-to-front retrieval rule provided no benefit over the naïve retrieval rule in uniform demand conditions.

Conclusion 5: *Larger storerooms necessarily have higher mean retrieval times.*

The length and width of a single I/O point storage system have a significant impact on the mean retrieval time of that system. In general, if storage system X is larger than storage system Y, X will have a higher mean retrieval time than Y for similar values of k, especially in the Naïve-Uniform, Naïve-Pareto, and MTF-Uniform scenarios. This finding is important because it is directly related to our choice of analyzing single I/O point designs. As the storeroom gets larger, the pallets on the opposite side of the storeroom from the I/O point have a longer distance to travel and therefore a higher total process time, which pulls the mean retrieval time of that system upwards.

Single I/O point or small square storage designs might not necessarily support the needs of engineers in designing future sea base storage systems. Since many factors and requirements go into the design of a sea base storeroom, flexibility in design will be important. Single I/O point designs limit flexibility and produce higher process times for items stored in the corners farthest from the I/O point. Utilizing multiple I/O point designs, on the other hand, increases flexibility by reducing mean retrieval times and allowing for use of larger higher density storage systems.

The packing algorithm always produces pallet configurations with at least three possible I/O points. This is a significant observation because of its impact on the storage density and response time trade-off. A large storage system with multiple I/O points is not only able to store more pallets than a single I/O point storage system that is half the size of the larger system but also do so with a mean retrieval time that will be at least as good as the smaller single I/O point system. For example, a 10 by 20, 4-deep storage system stores 168 pallets while a 10 by 10, 4-deep storage system stores 84 pallets. If the 10 by 20, 4-deep system has two or more I/O points, its mean retrieval time will be lower than the smaller single I/O point 10 by 10, 4-deep storage system. Because the larger storage system contains two or more I/O points, we have more flexibility for repositioning interfering pallets. As a result, larger multiple I/O point system can provide greater levels of sustainment, acceptable retrieval times, and may provide ship design engineers greater flexibility.

A. SUMMARY

The insertion of key AS/RS technologies aboard the sea base is a significant challenge. Without future technologies to support reduced manning initiatives and provide the ability to quickly and efficiently extract supplies from storerooms, the future sea base will be unable to support the concepts of Expeditionary Maneuver Warfare and Sea Basing. Given the capabilities the future sea bases must possess to support a force ashore, the implementation of these future technologies is necessary to achieve a selective offload capability utilizing storage densities between 70% and 85%. The higher density designs provide a bigger payoff in sustainment and only a slightly higher mean retrieval time. Not only does this still support a selective offload capability but also enhances the sea base's overall sustainment capability.

B. RECOMMENDATIONS FOR FOLLOW ON RESEARCH

This thesis is an effort examining the trade-off between high-density storage systems, their corresponding response times, and some simple retrieval rules that explore ways of decreasing a system's response time. The Office of Naval Research, the Naval Sea Systems Command, and Program Executive Office – Carriers are only some of the military organizations exploring research and technology in support of selective offload capabilities for future ships of the sea base. There are many additional opportunities for follow-on research associated. The following is a list of some of those areas..

- Analyze every I/O point for a variety of different configurations to determine the best I/O point for that configuration.
- Analyze the potential for improving mean process time by examining the use of two or more I/O points for a variety of different storage systems.
- Conduct additional analysis of the move-to-front storage system retrieval rule utilizing multiple I/O points.
- Expand and explore additional storage system retrieval rules.
- Consider reconfiguring the storeroom after each selection by repositioning the most recently selected pallets to the most accessible areas.
- Analyze how each configuration performs under differing utilization rates in an M/G/1 or G/G/1 queuing system.
- Simulate the entire material handling process on an MPF(F) ship to determine where bottlenecks in the process occur.

APPENDIX A. ALGORITHM FILL-AND-ROTATE

Additional detail concerning the packing algorithm described below can be found in Reference 26.

Algorithm 1 *FILL-AND-ROTATE*

Requires: $n \geq m,\ k < (m-1)/2$

Ensure: The grid is oriented with the *n*-long axis at the bottom.
{ $p_1, p_2, p_3,$ are the number of unassigned rows from the bottom to the top in their respective orientations}

Assign a *k*-deep row of items on the bottom, plus one aisle; Rotate the grid counter-clockwise; $p_1 = n$.

Assign a *k*-deep row of items on the bottom, plus one aisle; $p_1 = p_1 - (k+1)$.

while ($p_1 \geq 2k+1$) **do**

  Assign a $2k$ -deep row, plus one aisle;
  $p_1 = p_1 - (k+1)$.

end while

if ($p_1 \leq k$) **then**

  Assign a p_1 -deep row and **STOP**.

else { $k < p_1 \leq 2k$ }

  Rotate the grid counter-clockwise; $p_2 = m - (k+1)$.

  if ($p_2 > 2k+1$) **then**

    Assign a k -deep row on the bottom plus one aisle; $p_2 = p_2 - (k+1)$

  else

    while ($p_2 > 2k+1$) **do**

      Assign a 2*k*-deep row, plus one aisle;
      $p_2 = p_2 - (2k+1)$;

    end while

  if ($k < p_2 \leq 2k$) **then**

    Assign an aisle and a $p_2 - 1$ -deep row and **STOP**.

  else { $p_2 \leq k$ }

    Rotate the grid clockwise; assign a p_2 wide and k -deep row;
    $p_3 = p_1 - (k+1)$

    if ($p_3 \geq 1$) **then**

      Assign a $p_3(p_2 - 1)$ block in the remaining space; **STOP**.

    else

    STOP.

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APPENDIX B. NM + MCP PROCEDURE

The procedure by Nelson and Matejcik (1995), herein after referred to as NM + MCB, is described in detail below. [Ref 21, p 143] The parameter *k,* used in the procedure below, is not related to the accessibility constant (*k)* used in this thesis. The value *k* in the NM + MCB procedure is related to the number different storage systems being compared.

Notation:

- i : 1, 2, …, k storage system configurations.
- j : 1, 2, …, n_o replications per configuration.
- n_o : Initial sample size
- $1-\alpha$: Desired probability of correct selection
- δ : Indifference zone parameter
- g : The equicoordinate critical point of the equicorrelated multivariate central T-distribution where $g = T^{(\alpha)}_{k-1,(k-1)(n_o-1),0.5}$
- Y_{ij} : Average of the observations from the j^{th} replication of i^{th} design.
- u_i : Expected performance measure of alterative i where $u_i = E[Y_{ij}]$.
- σ_i^2 : Variance of the observed performance measure of alternative i from one replication where $\sigma_i^2 = Var[Y_{ij}]$.
- $\bar{Y}_{i\bullet}$: Sample mean of the i^{th} design where $\bar{Y}_{i\bullet} = \sum_{i=1}^{no} Y_{ij} / n_o$
- $\bar{Y}_{\bullet j}$: Sample mean of the first set of replications where $\bar{Y}_{\bullet j} = \sum_{i=1}^{k} Y_{ij} / k$
- $\bar{Y}_{\bullet\bullet}$: Sample mean of the entire set of observations where $\bar{Y}_{\bullet\bullet} = \sum_{i=1}^{k} \sum_{i=1}^{no} Y_{ij} / kn_o$.
- S^2: Approximate sample variance of the difference of the sample means where $S^2 = \dfrac{2\sum_{i=1}^{k} \sum_{i=1}^{no} (Y_{ij} - \bar{Y}_{i\bullet} - \bar{Y}_{\bullet j} - \bar{Y}_{\bullet\bullet})^2}{(k-1)(n_o-1)}$
- N: Final Sample size where $N = \max(n_o, \lceil (gS/\delta)^2 \rceil)$

The steps of the NM + MCB procedure:

1. Specify the constants $\delta, \alpha,$ and n_o. Find $g = T^{(\alpha)}_{k-1,(k-1)(n_o-1),0.5}$.

2. Take an i.i.d sample $Y_{i1}, Y_{i2}, \ldots, Y_{in_o}$ from each of the k systems using CRN's.

3. Compute the approximate sample variance S^2.

4. Compute the final sample size N.

5. Take N - n_o additional i.i.d observations from each system, using CRN's.

6. Compute the overall sample means $\bar{\bar{Y}}_i$.

7. Select the system with the smallest sample mean $\bar{\bar{Y}}_i$ as best.

8. Simultaneously form the MCB confidence intervals as follows:

$$u_i - \min_{i \neq j} u_j \in$$
$$\left[\ (\bar{\bar{Y}}_i - \min_{j \neq i} \bar{\bar{Y}}_j - \delta)^{-}, (\bar{\bar{Y}}_i - \min_{j \neq i} \bar{\bar{Y}}_j + \delta)^{+} \ \right]$$
$$for \ i = 1, 2, \ldots, k.$$

APPENDIX C. RETRIEVAL TIME DISTRIBUTION PLOTS

The following plots illustrate the distribution of retrieval times across the best six $k = 3$ designs, the best five $k = 4$ designs, and the best seven $k = 5$ designs. The best $k = 1$ and 2 designs were not included since those plots did not provide as much interesting information since most of the pallets are already located one pallet away or directly adjacent an aisle. The darker shades indicate higher retrieval times. One might assume that all pallets adjacent an aisle location would be shaded a lighter color like those pallets near the I/O point. However, storage systems with a single I/O point penalize locations furthest from the I/O point. Any pallet located further from the I/O point is automatically shaded darker to represent the increased travel time associated with retrieving that pallet. These plots illustrate the locations associated with the highest processing times.

A. BEST SIX k = 3 DESIGNS

m x n* *k = 3	**Position**	**Pallets**	**Total Pallet Locations**	**Density**	**Mean Retrieval Time**
8 x 8	Top Left	51	64	0.797	136.09
8 x 9	Top Right	57	72	0.792	140.28
8 x 10	Bottom Left	63	80	0.788	145.81
8 x 11	Bottom Right	69	88	0.784	158.19

Table 19 Retrieval Times of the Best Six k = 3 Designs

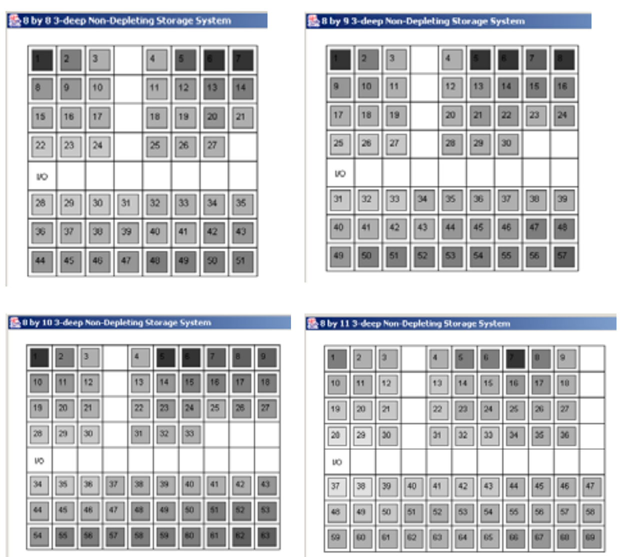

Figure 37 Distribution of Retrieval Times Illustration (k = 3), Part 1

m x n *k = 3*	Position	Pallets	Total Pallet Locations	Density	Mean Retrieval Time
9 x 9	Left	64	81	0.790	149.7
9 x 10	Right	71	90	0.788	158.07

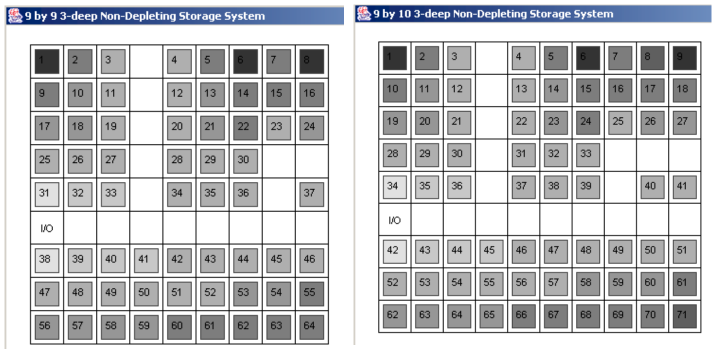

Figure 38 Distribution of Retrieval Times Illustration ($k = 3$), Part 2

B. BEST FIVE $k = 4$ DESIGNS

m x n *k = 4*	Position	Pallets	Total Pallet Locations	Density	Mean Retrieval Time
10 x 10	Top Left	84	100	0.840	171.66
10 x 11	Top Right	92	110	0.836	176.44
11 x 11	Bottom Left	101	121	0.835	186.44
11 x 12	Bottom Right	110	132	0.833	191.80

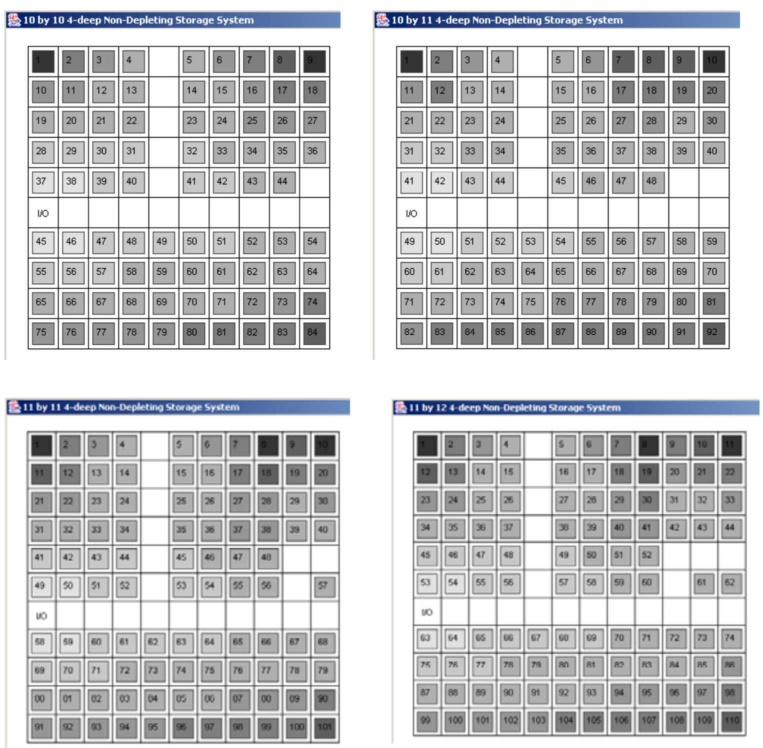

Figure 39 Distribution of Retrieval Times Illustration ($k = 4$), Part 1

m x n *k = 4*	Pallets	Total Pallet Locations	Density	Mean Retrieval Time
10 x 12	100	120	0.833	183.57

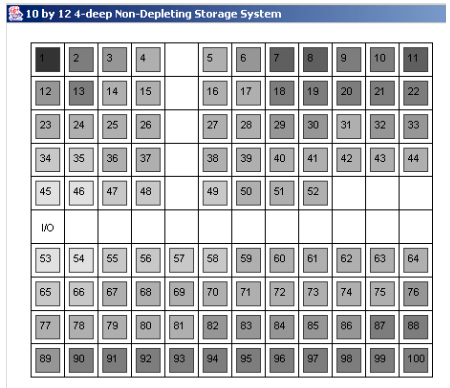

Figure 40 Distribution of Retrieval Times Illustration (k = 4), Part 2

C. BEST SEVEN k = 5 DESIGNS

m x n	Position	Pallets	# Locations	Density	Retrieval Time
12 x 12	Top Left	125	144	0.868	211.63
12 x 13	Top Right	135	156	0.865	216.93
12 x 14	Bottom Left	145	168	0.863	220.24
12 x 15	Bottom Right	155	180	0.861	224.98

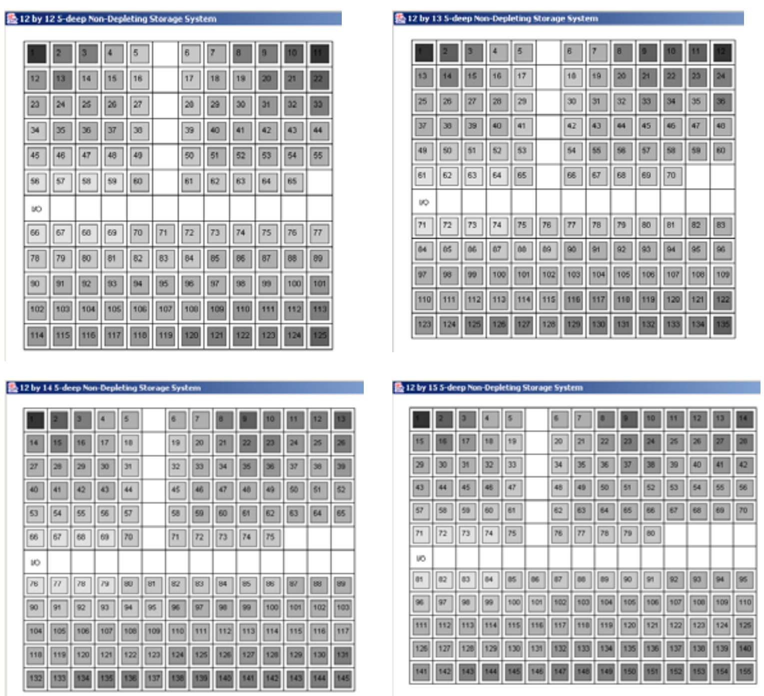

Figure 41 Distribution of Retrieval Times Illustration (k = 5), Part 1

m x n *k = 5*	**Location**	**Pallets**	**Total Pallet Locations**	**Density**	**Mean Retrieval Time**
13 x 13	Bottom Left	146	169	0.864	223.69
13 x 14	Bottom Right	157	182	0.863	228.66
12 x 16	Top	165	192	0.859	232.25

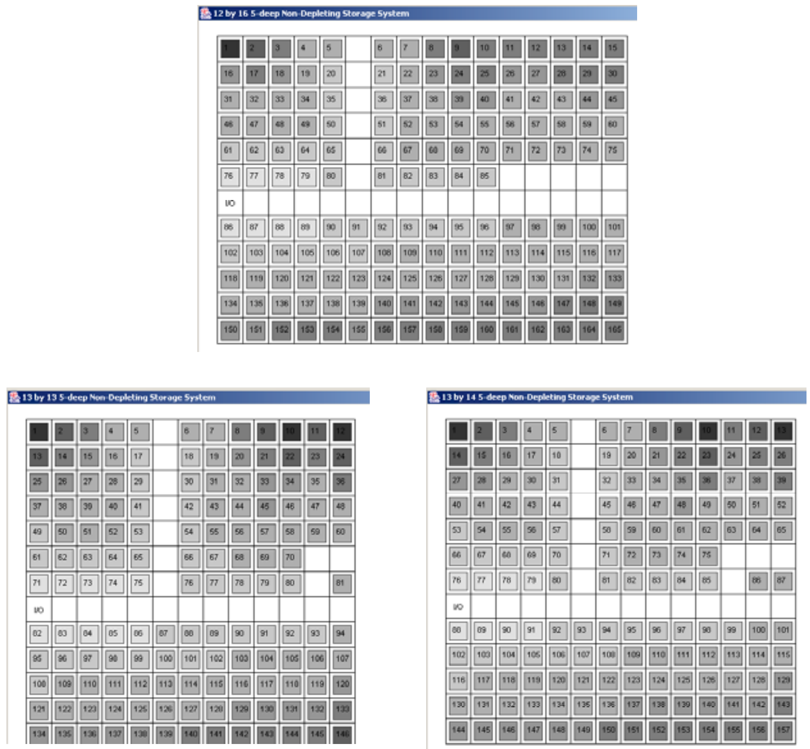

Figure 42 Distribution of Retrieval Times (k = 5), Part 2

APPENDIX D. VARIOUS STORAGE CONFIGURATIONS

The following plots illustrate different designs produced by the packing algorithm, Fill-And-Rotate, than those already illustrated throughout the thesis. Each design has at least three I/O points and all have in common a *k* set of rows on the bottom and a *k* set of columns on the left side just above the I/O point. The different shading of these plots is meant to illustrate the distribution of retrieval times based on their location in the configuration. The darker shades indicate higher retrieval times.

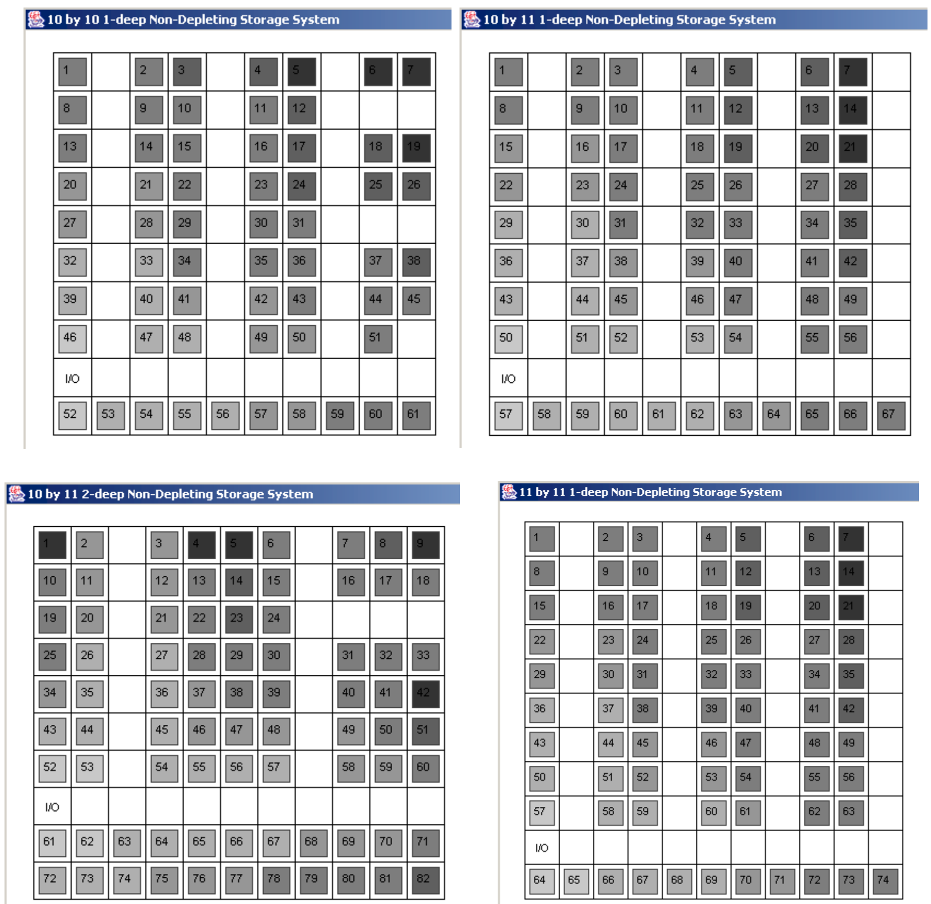

Figure 43 Various Storage System Designs, Part 1

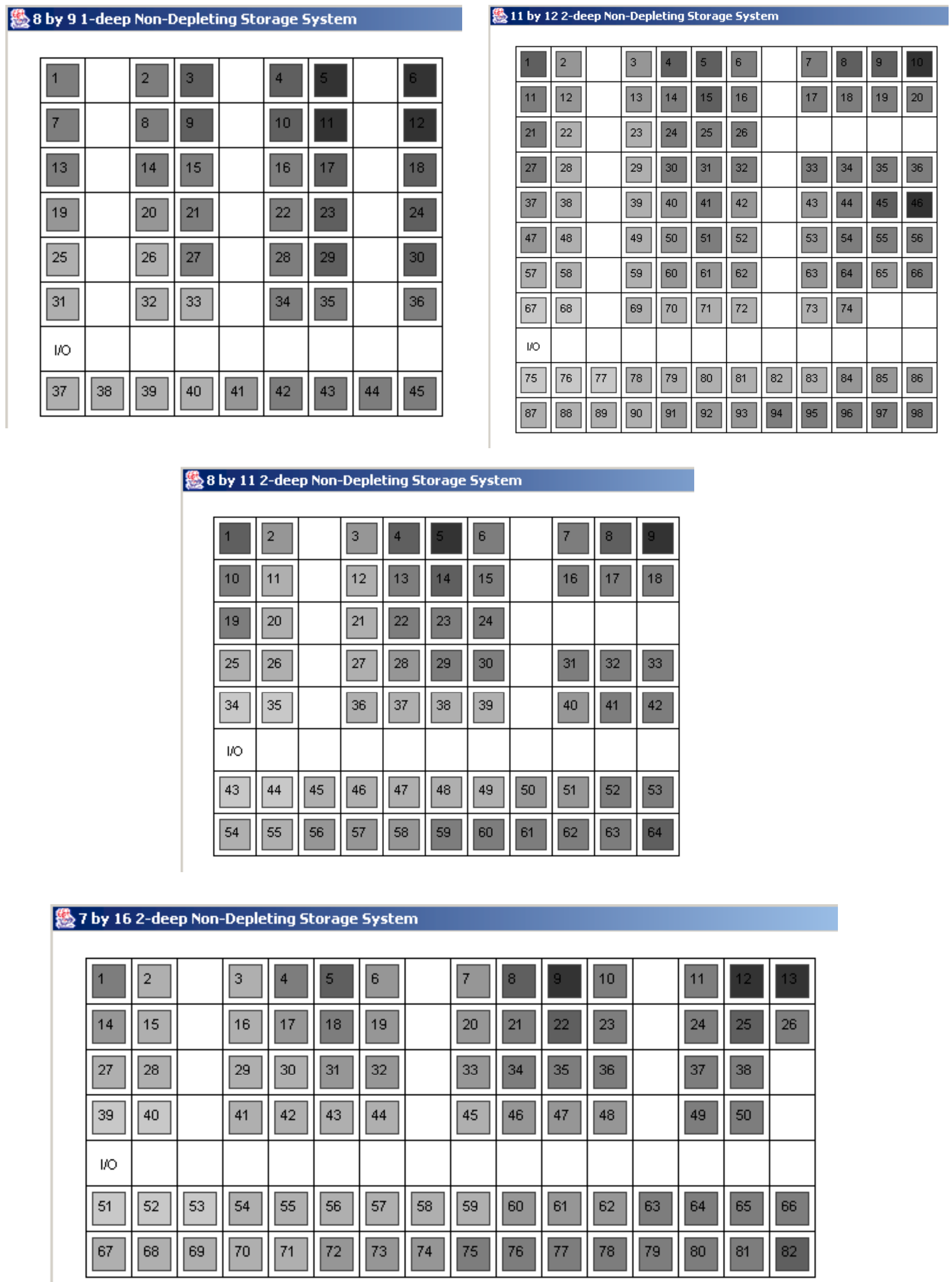

Figure 44 Various Storage System Designs, Part 2

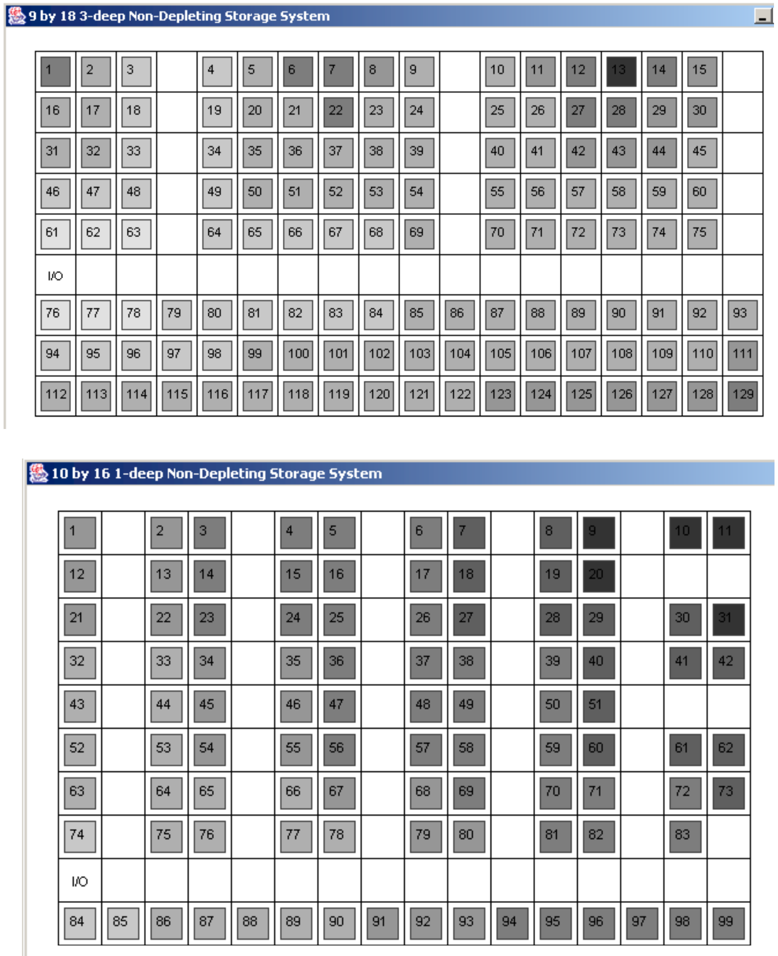

Figure 45 Various Storage System Designs, Part 3

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